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EXAMINATION OF MONTHLY WET SULPHATE DEPOSITION BY A LAGRANGIAN MODEL AND ITS APPLICATION TO STUDY THE EFFECTS OF SOURCE CONTROL ON RECEPTORS

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SYNOPSIS

The Lagrangian long range transport model was applied to determine the change in sulphur deposition during the shutdown period of the Sudbury smelters.

Since the wet deposition measurements at receptor sites show significant monthly and annual variability, the ability of the model to simulate monthly deposition was determined before application to the INCO shutdown study. It was observed that the model successfully simulated the monthly wet deposition of sulphate at several receptors over a three year period.

The evaluated model was then executed at first by including all the sources and then excluding Sudbury, and the results were compared. The impact of the shutdown period of Sudbury, thus determined, can be described as follows:

1. The reduction in wet deposition of sulphate is approximately 16 percent in the Muskoka-Haliburton area. The change is smaller at other distant receptors.

2. The change in dry deposition in Muskoka-Haliburton area is approximately 20 percent for SO_2 and 10 percent for sulphate.

3. Percentage contributions of Sudbury to wet and dry deposition of sulphur have values similar to the above when averaged over a three year period.

PKM/mb/MOD1-4

INTRODUCTION

One of the principal uses of a model of atmospheric interactions is in conducting controlled experiments which cannot be performed in the field. The atmosphere is too vast and complex and the energy levels are much too great to be confined into laboratory-like experiments. When we wish to know how the wet deposition would be affected by a change in distribution of emission sources, it is useful to be able to keep the meteorological factors the same while changing only emissions. A model can perform this type of simulation. This is a controlled experiment which is difficult to duplicate in field observations.

The Lagrangian trajectory model of long range transport of atmospheric pollutants has been employed to simulate monthly average wet deposition for the years 1978, 1979, 1980. These are the years for which meteorological data was available. The model has been described in detail in Ellenton et al (1982, 1984). In the model, trajectories are initiated from each of 182 source centres in North America, every three hours. Trajectory duration is ninety-six hours. The model domain extends from the Rocky mountains in the west, to the east coast and from Florida in the south, to Hudson Bay. The transport of sulphur oxide emitted from each of the sources is computed along each trajectory, with chemical change and removal to the earth's surface in rain and in dry conditions. The wet deposition computed at any location is the sum of the contribution from all sources for the specified period of time. In this simulation the monthly variation in wet deposition depends only on changing meteorology because annual emission values are used. This is with one exception. For the Sudbury source, the monthly emissions change according to the strike/shutdown months in 1978 and 1979.

It is expected that when emissions are reduced, long term trends in wet deposition will decrease as a result. This reduction will not necessarily be evident in the measurements in the short term, however, due to changing meteorology such as natural variability in rainfall amount and wind flow patterns. To illustrate this argument the probability of observing a change in the field measurements of wet deposition, given a certain reduction in SO_2 emissions has been computed in the Appendix under some assumptions of the wet deposition statistics. It is shown that the wet SO_4^{2-} deposition at a receptor in a given year, when emissions are reduced by a certain fraction, has a finite probability of showing an increase over the corresponding values of the previous year rather than the expected decrease. Also shown in the Appendix is that the emission reduction must remain in effect for a very long period, before the observed mean wet deposition of SO_4^{2-} shows a reduction over the previous years' mean.

In model simulation one has the flexibility of reintroducing the sources after the model results with reduced emissions have been properly evaluated with the field data. This gives the wet deposition results for both, with and without the reductions in emission, which enables us to compute the wet deposition changes per annum, or at shorter time scales. This would be difficult to obtain from field measurements alone.

The purpose of this paper is to illustrate this point for the year 1979 when INCO, one of the largest SO_2 emitters, was shut down for a total of six months. The analysis follows two directions. First, the model must successfully simulate the monthly wet SO_4^{2-} deposition trend and second it must compute the change in wet SO_4^{2-} deposition at receptors in 1979 over the same period if INCO were operational throughout this year.

In this report the monthly variation in simulated wet deposition is compared with measured wet deposition for locations and periods of time when it is available. The significant variation in measured deposition from month to month may be seen in Figures 2 to 25. The strong influence that meteorological factors have on deposition is evident from the facts that the model simulates these monthly trends with considerable success and that the monthly variations in simulated deposition depends only on the variability of the meteorology, since the emissions do not change from month to month (with the Sudbury exception already noted).

Because of the complexities of the atmosphere no two sets of conditions are exactly alike. The simplifications of these complex interacting atmospheric influences in a practical model have to be designed with care to ensure that the model successfully simulates those aspects of the atmosphere it is intended to replicate. Also, comparison of model simulations with observed data is essential in the evaluation of its performance. One must therefore look at both the monitored data and model simulations when assessing a situation.

SIMULATION OF MONTHLY TRENDS

The Lagrangian trajectory puff model of long range transport of atmospheric pollutants has been developed to the point where simulated annual average wet deposition of sulphur oxides for 1979 compares well with measured values. A detailed description of the model including tables showing comparisons of model computed annual average ambient concentrations and annual wet depositions is given in Ellenton et al (1982). Comparison of computed seasonal trends in wet deposition during 1979 with the seasonal variability in observed values at monitors in the APN, CANSAP and MAP3S networks (Ellenton et al, 1984) has shown good agreement.

In order to use the model to estimate the change in wet deposition during a shut-down period at INCO, depositions averaged over the shutdown period, i.e., less than a year, are needed. It will be necessary, first, to compare simulated and monitored values of wet deposition to determine whether the model can replicate month to month variability in wet deposition. For the analysis which follows, the trajectory and wet deposition calculations are based on a new and much improved meteorological data set for the years 1978, 1979 and 1980.

An analysis of monthly trends during 1978, 1979 and 1980 is given here, using wet deposition data from the MOE APIOS network and the APN network in Ontario and the MAP3S network in neighbouring states. Figure 1 shows the locations of the monitors in these networks. Because of the scale of the long range calculations, the model predicts values only at distances greater than 127 km from a source. Hence, comparisons were made with values from monitors located at least 127 km away from the INCO plant at Sudbury.

In computing monthly variability, it is assumed that emission levels do not show marked monthly variations. This assumption may affect the impact of a few specific sources on some receptors. This will not affect the overall results significantly. Model values of monthly wet deposition include a background of 50 mg SO_4/m^2 month. The generally accepted background due to biogenic emissions and other small emissions not included in the model inventory is 6 kg/ha.year. This was apportioned equally to all months since it is not known what the monthly variation in background is.

Figures 2 to 5 show comparisons in the trends of monthly wet deposition of sulphur oxides as simulated by the model for 1978, and as observed at the monitors. Fig. 2 shows monthly wet deposition as simulated by the model for the Muskoka - Haliburton areas (Dorset, Eagle Lake, Vankougnet and Carnarvon) compared with bulk deposition for the area as reported by Scheider et al (1980). Only bulk deposition data is available in the area for this time. Wet deposition is necessarily less than bulk deposition which is the sum of wet plus some unknown dry deposition. Comparing the two sets of data, monthly rises and falls show similar patterns throughout most of the year. August is an exception when the very high measured value is not matched by the simulated value. Also the December decrease in the simulated deposition is in opposition to the rise in the measured value for this month. At Parry Sound (Fig. 3) model values are lower than measured deposition (Special Studies, 1982) but all monthly pairs of values agree within a factor of two except December. The relatively high value of deposition in September occurs because the measuring period extended from September 1 to October 4. This also means that the shortened measuring periods for October, Oct. 5-31 resulted in relatively low deposition. Model simulation periods are for the calendar months so direct comparison is difficult. The peaks and troughs of measured and model simulated values are well correlated, most notably from May to October when these variations are quite marked. The model appears to exhibit opposing trends to measured deposition in two intervals, March to April and October to November. However, the measured data may have an uncertainty of approximately 30%, thus not allowing us to associate significance to this difference.

In the MAP3S network, at Whiteface Mt. (Fig. 4) and Penn State (Fig. 5) simulated wet deposition and measured values (MAP3S/RAINE, 1980) are of similar magnitude. Monthly increases and decreases in modelled and measured deposition are well correlated except for two monthly intervals in each figure. At Whiteface these are February to March and April to May. At Penn State, the intervals are March to April and September to October. Once again, given the uncertainty in measurements, it is difficult to say if this difference is real.

Figs 6 to 18 show wet deposition comparison for 1979. At Parry Sound (Fig. 6), the overall trends throughout the year are similar. In April the measured deposition is greater than 500 mg SO_4/m^3. Although the simulated value also rises it is less than 300 mg SO_4/m^3. As a result, the April to May decrease is not simulated. Opposing trends in the two sets of values appear in July - August - September, when the measured August value is relatively low.

Values for Simcoe (Fig. 7) show correlated rises and falls in the simulated and measured (Vet et al, 1981) wet deposition. The very high measured value in August of 772 mg SO_4/m^2 appears in the model as a more modest amount, 497 mg SO_4/m^2. We note here that the August measured wet deposition at Long Point (see Fig. 12) which is located about 30 km to the southwest of Simcoe is approximately 300 mg SO_4/m^2. This represents a large difference in measured values in a short distance. The difference is not, in this case, the result of precipitation spatial variation alone, but is rather due to high values of both rainwater concentration and rain depth at Simcoe. Concentration of sulphate in rainwater in August at Simcoe is reported as 88.2 mg/l, while at Long Point it is 5.9 mg/l. This difference over a short distance is questionable. Precipitation depths at the two sites are 94.8 and 51.4 mm at Simcoe and Long Point respectively. The model computed wet deposition for Simcoe is about mid-way in value between the wet deposition reported for these two locations. At Kingston (Fig. 8) monthly variations are correlated between modelled and measured values during the period September through December when measured trends are available. Woodbridge (Fig. 9) also shows matching values except in July. Vet et al. (1981) however report a sample malfunction during this month. For this reason, they did not make a comparison between networks for July; hence, it is appropriate not to make a comparison with the modelled value. Fig. 10 shows wet deposition at South Baymounth with excellent comparison between model and measured values.

At Dorset, (Fig. 11a) the trends in the two sets of deposition values do not compare well. Although values for all months agree within a factor of two the monthly upward and downward trends show significant opposite tendencies August to September to October intervals. However, sampler malfunction was reported by Vet et al (1981) in both August and October. Fig. 11b shows comparison of the same model values with wet deposition measured by the co-located CANSAP monitor. The CANSAP measured value in August is considerably lower than the MOE value and in October and Novmeber the CANSAP values are much higher than the MOE values. The model monthly trends agree with CANSAP trends for all available months. Magnitudes are similar too, except in November when the model and MOE magnitude are the same.

At Long Point (Fig. 12) in the APN network, trend analysis is not possible in measured data during the first half of the year due to missing wet deposition values for February, April and June. Good comparison between modelled and measured (Barrie et al 1980) trends is evident from September to December. The high simulated deposition in August compared with the measured value creates opposing trends in July to August and August to September. As discussed above, nearby Simcoe reported measured wet deposition in August as 772 mg SO_4/m^2. So the August value is open to question. At Chalk River (Fig. 13) the trend analysis begins in April, since February and March measurements are not available. The simulated and measured values agree in magnitude but the trends do not agree except in October to December. In April to May both values rise, but the increase in measured wet deposition is much greater than in the simulated value. At ELA-Kenora (Fig. 14) there is excellent agreement between simulated and measured magnitude and trends throughout the year.

Comparative monthly wet deposition for MAP3S monitor locations in 1979 is shown in Figs. 15 to 18. At Whiteface Mt. (Fig. 15) model values match the measured deposition very well both in magnitude and in monthly trends. The small opposing trend in January to February is not significant since it is within the possible error range in the measurement. The measured deposition for November is not available, but the downward trend in measured values October to December also appears in model values. Fig. 16 for Ithaca shows comparable model and measured values except in July when the measured wet deposition is much higher and the upward trend is not simulated. Small opposing trends occur in March to April but these differences are not significant . At Penn State (Fig. 17) model values exceed measured values for most months. The monthly trends in the two sets of values are correlated throughout the year except in October-November. There is a signficant trends difference in October to November. At Oxford Ohio (Fig. 18), from February to June, model values are greater than the measured wet deposition, but with matching upward and downward tendencies except the March decrease. The very large measured deposition in July is to be compared with a much smaller simulated increase. Values are approximately equal to each other in August November and December. The intermediate trends during the period cannot be compared because September and October measurements are missing.

For 1980 at Dorset (Fig. 19) good correlation is shown between measured and model values for all months except June and August when the higher measued values in these months are not simulated. At Parry Sound (Fig. 20) measured data is available only for the period January to April. Measured deposition is much greater than simulated deposition in January but the values are roughly comparable in March and April. With a considerably larger increase February to March in the model values. Fig. 21 for Kingston shows the five months, January to May when measured data were reported. Excellent agreement between monitored and model-computed values occur throughout this period. For Simcoe (Fig. 22) CANSAP measurements are available for January to May. Here again modelled and measured values agree well.

Fig. 23 shows Long Point (APN) data. Simulated and measured (Barrie et al, 1981) values show generally good agreement. There are only two intervals in which significantly different trends occur. These are March to April and August to September. At Chalk River (Fig. 23) the overall trend in measured values is well simulated. As Dorset (Fig. 19), the model values in summer are considerably lower than the measured values, but they still agree within a factor of two. Trends are similar except for three intervals, March to April and May to June to July. Fig. 24 for ELA-Kenora shows comparable monitored and simulated values throughout the year, as was the case for this location in 1979 (Fig. 14). The small trend differences which occur are not significant, being within the possible error range of the measurements. Model values are higher than measured values. This is probably because the assumed background of 50 mg/m^3 for all locations is too high for this region.

These monthly analyses for the three year period 1978, 1979 and 1980 show that the Lagrangian model simulation of monthly wet deposition is reasonably similar to wet deposition measurements for almost all locations with excellent agreement at some. This is in spite of uncertainties in both the measured data and the model parameters.

Fig. 26, a scatter plot of the ratio: measured/model-simulated wet deposition illustrates that this ratio is within the bounds of "factor of two" for more than 85% of the data pairs. The simulated values include a background of 50 mg SO_4/m^2 month which is equivalent to the generally accepted value of 6 Kg SO_4/ha.year apportioned equally over 12 months. Background deposition is attributable to biogenic emissions and emissions from small sources not included in the model.

Table 1 shows the mean and the standard deviations, of the difference between observed and modelled monthly wet deposition, for the periods of available data. The values arise from uncertainties in both model parameters and measurements, as well as the use of annual emissions in the simulations. For all sources except Sudbury monthly variations in emissions were not included in the model simulation. At Sudbury, emissions varied with the shutdown/strike periods at INCO. The values indicate the differences (measured - model deposition) which can be expected in model simulations on a monthly time scale.

The foregoing analysis demonstrates that the Lagrangian model can be a useful tool for examining wet deposition on a monthly time scale. The model can extend the information given by observations of deposition, providing further insight into the interactions of the emission and meteorological influences. Further, it suggests that controlled experiments conducted by the model maintaining all factors constant, while varying just one, e.g. emissions, can provide estimates of the effects on depositions with some degree of confidence.

MODEL EXPERIMENT FOR SHUTDOWN PERIOD

In 1979, a shutdown period at the INCO plant at Sudbury resulted in reduced emissions during the months January to May inclusive plus August. Wet deposition calculations in the monthly trends for 1979 (Figs. 6-18) were based on these conditions. The model has also been employed in a simulation using full emissions at Sudbury during these months while emissions from all other sources and meteorological influences remain the same. The full emission value is the monthly average for the operating months of 1979. The difference in wet deposition at the monitoring sites for the two cases, with and without emission at INCO Sudbury during the five months provides an estimate of the effect that reduced emissions at this one source has on receptors.

Table 2 shows the percentage change in wet deposition of sulphur estimated by the model, expressed as a reduction from full emission vs no emission at INCO at Sudbury averaged over the six month period January to May and August 1979. The values are plotted on a map in Fig. 27. The effect is greatest close to Sudbury, as would be expected, with the percentage decrease estimated at 24% for Parry Sound and 25% for South Baymouth. At Dorset the value is 16%. At other farther locations in Ontario the estimated reduction is less than 10%.

The experiment has been extended to assess the effect of reduced emissions over a longer period. Table 2 and fig. 28 shows the percentage reduction for the full three year period 1978, 1979, and 1980. It will be noted that these values of percentage reduction are similar in magnitude to those shown in Fig. 27 for the 1979 non-operational period.

Contours of Percentage Reduction in Wet Deposition

Figure 29 illustrates the geographical distribution of the reduction in wet sulphur deposition using the model for a controlled experiment for the year 1980 when meteorological conditions and all emissions except INCO were held constant. The only change is thus the operation or non-operation of INCO emission during monthly simulations for the year. Note that the values given in Fig. 28 were for a three year period 1978-1980 so they may differ somewhat from these single year values. Deposition for both operating and non-operating cases included a background of 6 kg SO_4/ha.year, before the percentage difference was computed.

The area of greatest reduction lies to the north and northeast of Sudbury, in northern Ontario and Quebec. Much smaller percentage reductions occur south of Sudbury. The meteorological influences governing these contours are the patterns of wind flow and precipitation. Another influence is the transport distance from other sources, many of which are clustered in the Ohio valley. Their transport distance to southern Ontario is shorter than to northern Ontario so that their contribution to wet deposition is greater in areas south of Sudbury than in areas to the north. This has the effect of making INCO's proportional contributions smaller in southern Ontario than in northern Ontario.

Contours of Percentage Reduction in Dry Deposition

An extension of the study to the estimate of dry deposition reduction is illustrated in Figs. 30 and 31 for SO_2 and SO_4 respectively for the year 1980. Dry deposition is computed in the model as the product of air concentration and a dry deposition velocity which varies seasonally. The dry deposition velocity for SO_4 is smaller than for SO_2, making the contribution of SO_2 dry deposition to the total the more significant of the two. The difference in the shape of the contours in the two figures is due mainly to the inclusion of a constant background SO_4 air concentration of 2 ug/m^3 in the calculation for Fig. 31. In Fig. 30 for SO_2 dry deposition the area most affected lies north of Sudbury in Ontario and Quebec. Wind flow patterns and the proportional contribution of other sources are the principal influencing factors on these contours.

Conclusions

Monthly variations in wet deposition of sulphur oxides, as simulated by the Lagrangian model of LRTAP, have been compared with measured values from three monitoring networks. Monthly rises and falls in modelled and measured wet deposition showed good agreement for most locations. Also, there was agreement within a factor of two for more than 85% of the pairs of values. These comparisons give confidence to the use of the model as an investigative tool on a monthly time scale.

The model is performing better on a monthly basis than expected, in view of the many uncertainties in model parameters. It is possible that the effects of the uncertainties and errors inherent in the calculations along individual trajectories tend to cancel out when averaged over a large number of trajectories. This lends confidence to our approach of computing wet deposition from the effects of many trajectories viewed as an ensemble.

With the exception of the reduced emissions from Sudbury during INCO's shutdown period, emissions from all sources were annual values. Hence the monthly variations in simulated wet deposition as shown in Figures 2 to 25 were due almost entirely to meteorological variations. These included changes in patterns of wind flow and precipitation, as well as seasonal variations in model parameters.

In order to estimate the effect on wet deposition of the shutdown of INCO emissions, a model experiment was carried out in which simulated wet deposition for the shutdown period during 1979 was recalculated using full emission at INCO, while maintaining all other model variables the same. Results indicate that the percentage decrease in wet deposition attributable to the 1979 INCO shutdown is about 16% in the Dorset area. The reduction is larger, closer to Sudbury, e.g. 25% at South Baymouth and the reduction falls off to 3% at Simcoe. Extension of the model experiment to calculate the effect of removing INCO emissions for a three year period resulted in slightly smaller reductions, i.e. 15% at Dorset and 22% at South Baymouth.

These results must be assessed in view of the uncertainties of model predictions. Further work in this area would be useful. Model results do provide, however, an additional tool to be used along with measurements. When wet deposition measurements taken over two different periods are compared, the effects of changing meteorology are usually great enough to obscure the effects of emission reduction at a single source over a short period of time. By using the model to maintain the same meteorology for simulations with and without INCO emissions, the consequences of emission reduction may be estimated.

References

Barrie, L.A., H.A. Wiebe, P. Fellin and K. Anlauf, 1980: The Canadian air and precipitation monitoring network APN: A description and results for November 1978 to June 1979; Canadian Atmospheric Environment Service Report AQMRB-80-002-T.

Barrie, L.A., H.A. Wiebe, K. Anlauf and P. Fellin, 1981; Results of the Canadian air and precipitation monotoring network APN: July 1979 to June 1980 Canadian Atmospheric Environment Service Report AQRB-81-026-T.

Barrie, L. A. 1981: Environment Canada's Long Range Transport of Atmospheric Pollutants Program: Atmospheric Studies; Report AWRB-81-021-T.

Barrie, L.A. 1982: Results of the Canadian air and precipitation monitoring networks APN: July 1980 to December 1981; Canadian Atmospheric Environment Service report AQRB-82-009-T.

Ellenton. G., B. Ley and P.K. Misra, 1982: Lagrangian model of the long range transport of sulphur oxides; Ontario Ministry of the Environment report API 008/82.

Ellenton, G., B. Ley and P.K. Misra, 1984: A trajectory puff model of sulphur transport for eastern North America; Atmospheric Environment; to be published.

MAP3S/RAINE Research Community, 1980: The MAP3S precipitation chemistry networks; statistical overview of the period 1976-1980; U.S.E.P.A. and U.S. Dept. of Energy contract #DC-AC06-76RLO 1980.

Special Studies Unit, Atmospheric Research and Special Programs Section MOE. 1982: Precipitation Quality and Wet Deposition in the Sudbury Basin: Sudbury Environmental Study Cumulative Precipitative Network Results; Supplementary Volume to SES 007/82.

Special Studies Unit, Atmospheric Research and Special Programs Section MOE 1983: Monthly /28 day cumulative precipitation chemistry listings June 1980-December 1981. Ontario Ministry of the Environment report ARB-53-83 ARSP.

Scheider, W.A., D.S. Jefferies and P.J. Dillon, 1980: Bulk deposition in the Sudbury and Muskoka-Haliburton areas of Ontario during the shutdown of INCO Ltd. in Sudbury; Ontario Ministry of the Environment Report.

Vet, R.J., W.H. Chan and M.A. Lusis, 1981; An intercomparison study of three precipitation sampling networks in Ontario-APOS, CANSAP and GLPN; Ontario Ministry of the Environment report ARB-002-81-ARSP.

APPENDIX

The following analysis shows that it is not possible, through measurements alone, to ascertain the consequences of shutting down a point source to the wet deposition of SO_4^{2-} at specific receptors. This is particularly so, when the net contribution of the source to the deposition is in the range of 0-20%.

The problem to address is not to determine the change from the previous year's deposition measurements when a point source is switched off for the entire period of the current year. The problem to address should be as follows:

"What is the net change in deposition at the receptor in the current year when the point source is switched off versus if it were operational".

The latter problem is answerable by the use of a validated model.

PROBLEM 1:

The mean deposition observed at a receptor is D Kg Ha^{-1} Yr^{-1}. The standard deviation based on annual deposition data is 0.5 D Kg Ha^{-1} Yr^{-1}.

What is the probability that in a given year the observed deposition is greater than or equal to 1.2 D?

SOLUTION:

Let us assume that the annual fluctuations about the mean are normally distributed.

Then, the probability density function for is given as follows

$$p(\epsilon) = \frac{1.02}{\sqrt{2\pi}\ \sigma} \exp\left[-\frac{\epsilon^2}{2\sigma^2}\right]$$

where σ = 0.5 D and the factor 1.02 is due to truncation of the distribtuion at $-\epsilon$ = D.

We require that ϵ is positive and that $|\epsilon| \gtrsim$ 0.2 D. In other words, Probability $(\epsilon > 0\ ,\ |\epsilon| > 0{\cdot}2D)$

$$= \int_{0\cdot 2D}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{\epsilon^2}{2\sigma^2}\right] d\epsilon$$

$$= \int_{0\cdot 2D/\sigma}^{\infty} \frac{1}{\sqrt{2\pi}}\, e^{-t^2/2}\, dt$$

$$= 0{\cdot}35$$

The above result shows that 35 out of 100 annual measurements will show an increase rather than a decrease when the emission reduction postulates a decrease at a receptor. Thus the probability of a single measurement not showing a change is rather high.

PROBLEM 2

Given the above variability in deposition measurement, how many years of data are needed to obtain a long term mean deposition to within 20% of the true mean?

SOLUTION:

Once again we assume ϵ to be normally distributed. Ideally, $\bar{\epsilon} = 0$. Let us suppose that we form a subset of ϵ by averaging over n years of data and call it $\bar{\epsilon}$, $\bar{\epsilon}$ is a random variable with zero mean, and standard deviation, $\sigma/\sqrt{n}$.

We require that $|\epsilon| \leq 0{\cdot}2$ whether ϵ is positive or negative, with a probability of 95%.

$$0{\cdot}25 = \int_{-0{\cdot}2D}^{0{\cdot}2D} \frac{\sqrt{n}}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{n^2\bar{\epsilon}^2}{2\sigma^2}\right] d\bar{\epsilon}$$

$$n \simeq 22$$

Thus, a record of 22 years is required in the minimum to obtain a mean which is within ±20% of the true mean.

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Table 1
Difference Between Modelled and Measured Monthly Wet Deposition

Location	N	O Mean of observed deposition $\frac{\text{mg } SO_4/m^2}{\text{month}}$	M Mean of modelled deposition $\frac{\text{mg } SO_4/m^2}{\text{month}}$	O-M Mean of difference $\frac{\text{mg } SO_4/m^2}{\text{month}}$	Standard deviation of (O-M) $\frac{\text{mg } SO_4/m^2}{\text{month}}$
Dorset	17	277	258	-19	147
Parry Sound	27	358	264	-93	117
Kingston	11	188	220	+32	60
Simcoe	7	310	342	+32	153
Long Point	21	312	331	+19	70
Whiteface Mt.	20	190	212	+22	73

Table 2

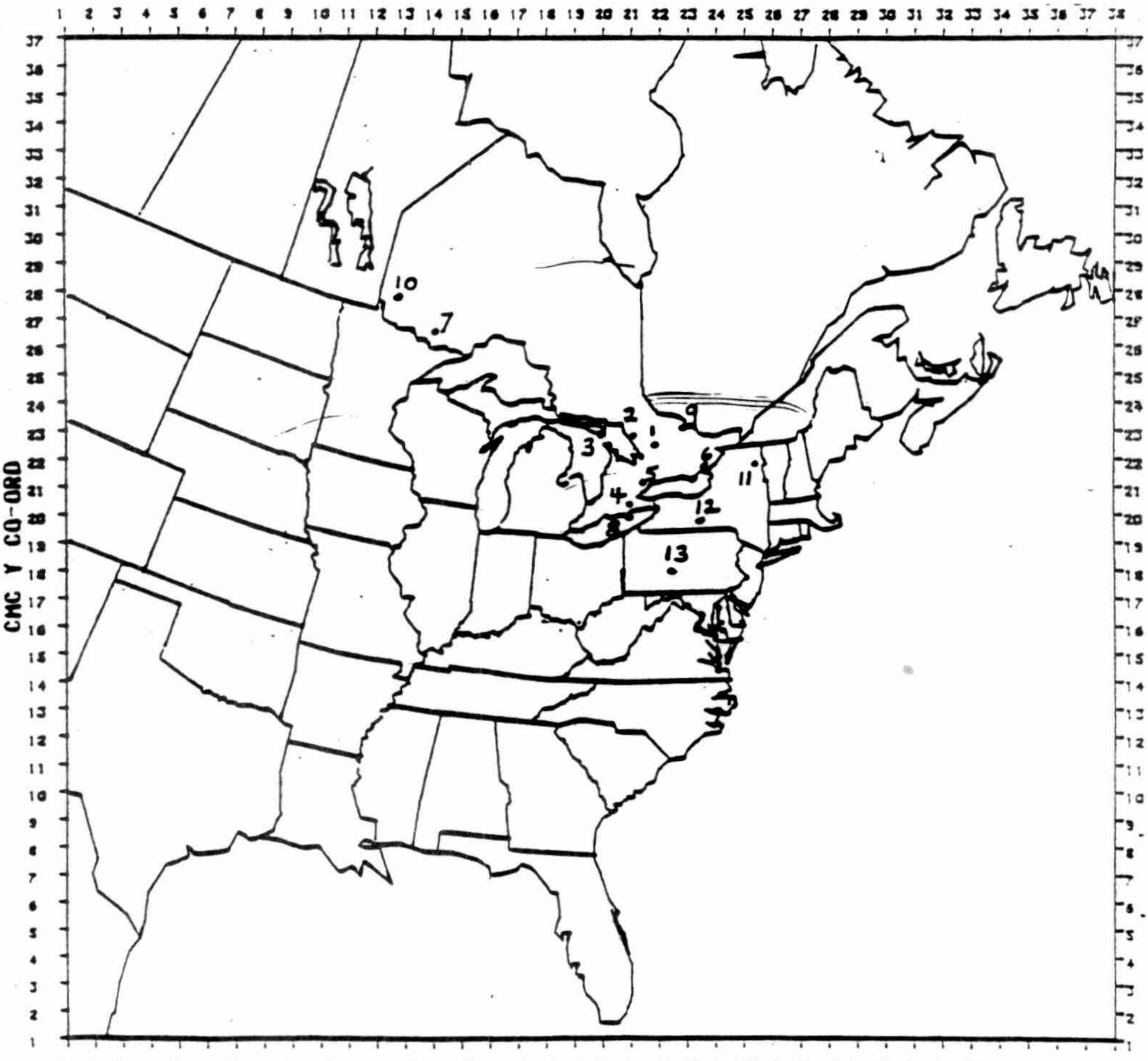
Model Experiment

Simulated Reduction in Wet Deposition SO_4
INCO Emission Operating* and Not Opertating;
All other Emissions and Meteorology Remain the Same

Location	1979 January to June and August mg SO_4/m^2** 6 months Reduction/oper.	(%)	1978-1980 all months kg SO_4/ha** 3 years Reduction/oper.	(%)
Dorset, Ont.	44/269	(16)	15/99	(15)
Parry Sound, Ont.	72/299	(24)	23/108	(21)
Kingston, Ont.	10/222	(5)	4/86	(5)
Simcoe, Ont.	11/334	(3)	3/122	(2)
Woodbridge, Ont.	19/293	(6)	6/105	(6)
S. Baymouth, Ont.	78/309	(25)	23/105	(22)
Atikokan, Ont.	4/139	(3)	1/44	(2)
Long Point, Ont.	10/342	(3)	3/125	(2)
Chalk River, Ont.	28/229	(12)	10/87	(11)
ELA-Kenora, Ont.	1.6/103	(2)	0.5/35	(1)
Whiteface Mt., N.Y.	5/193	(3)	2/75	(3)
Ithaca, N.Y.	6/257	(2)	2/95	(2)
Penn. State, Penn.	4/119	(1)	1/119	(1)

* hypothetical INCO monthly emissions used in model calculations during actual non-operating months is average of emissions during actual operating months for the specified year.

** wet deposition includes background of 50 mg SO_4/m^2 month for all months, for both cases: INCO operating and not operating.



1	Dorset	6	Kingston	11	Whiteface Mt.
2	Parry Sound	7	Atikokan	12	Ithaca
3	South Baymouth	8	Long Point	13	Penn State
4	Simcoe	9	Chalk River		
5	Woodbridge	10	ELA Kenora		

Figure 1 Locations of monitoring sites; measured values of wet deposition of sulphur at these locations were compared with values simulated by the model in the evaluation of simulated monthly wet deposition.

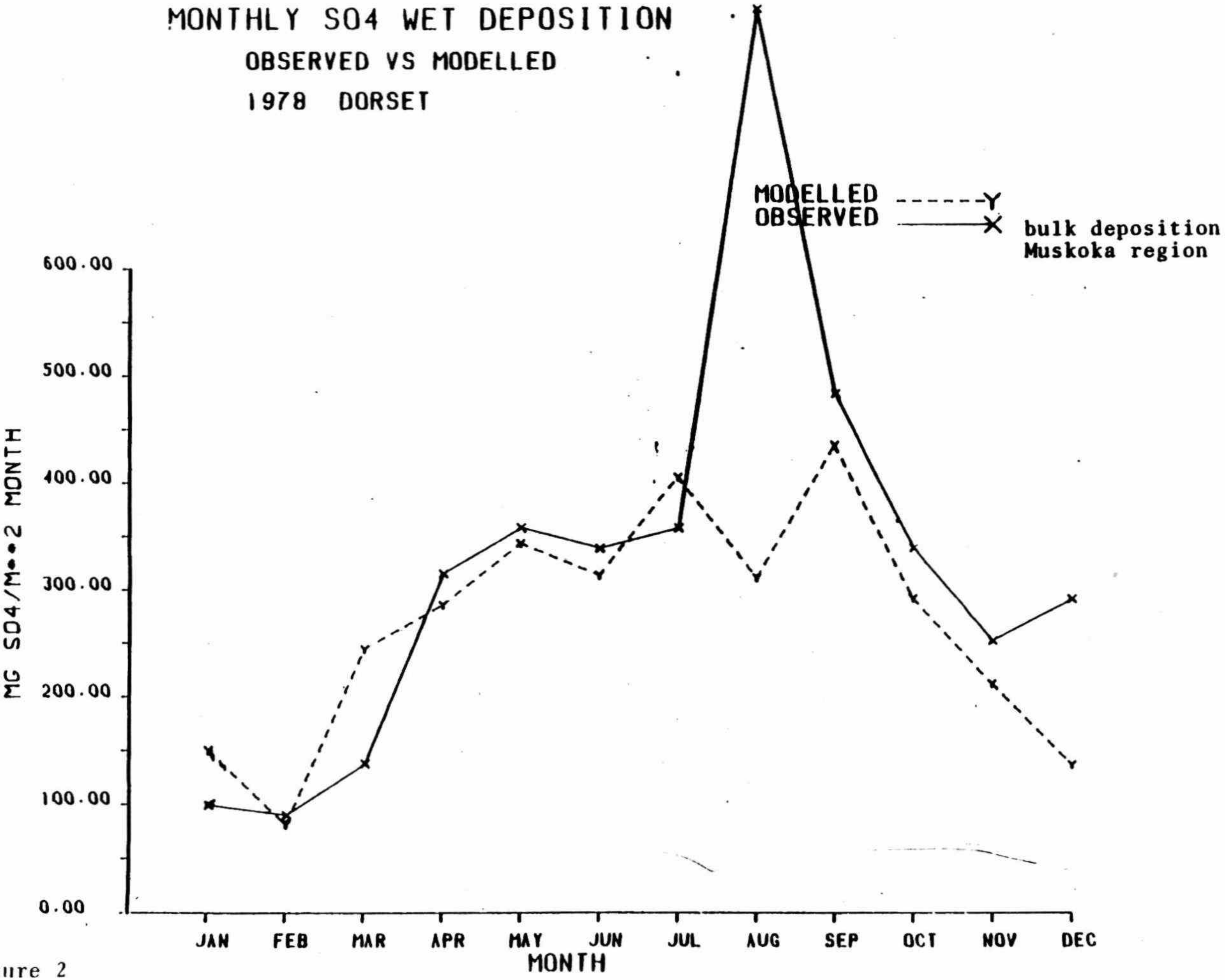

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1978 DORSET
MODELLED
Y
OBSERVED
X
bulk deposition
Muskoka region
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 2

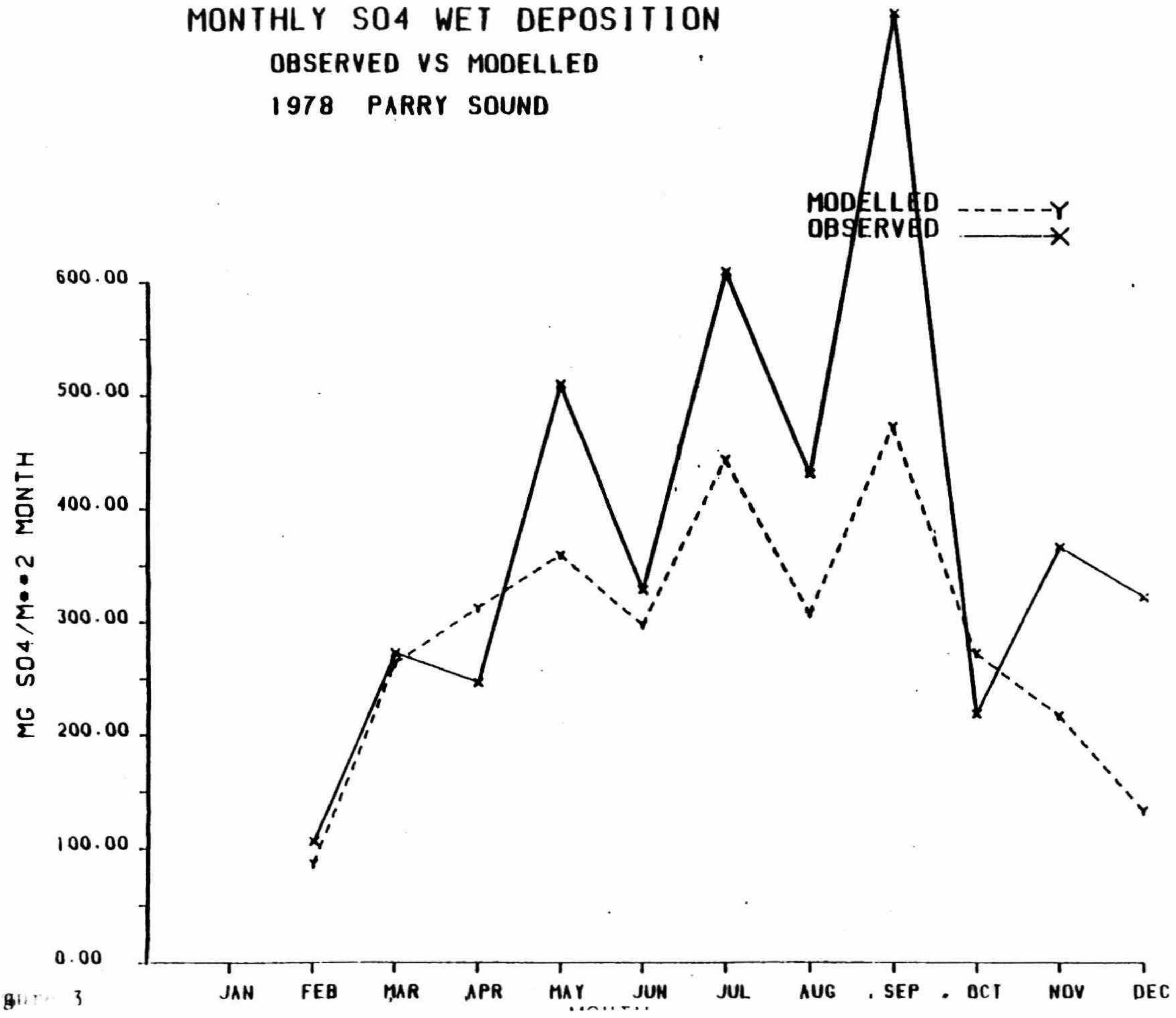

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1978 PARRY SOUND
MODELLED Y
OBSERVED X
MG SO4/M**2 MONTH
600.00
500.00
400.00
300.00
200.00
100.00
0.00
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Figure 3

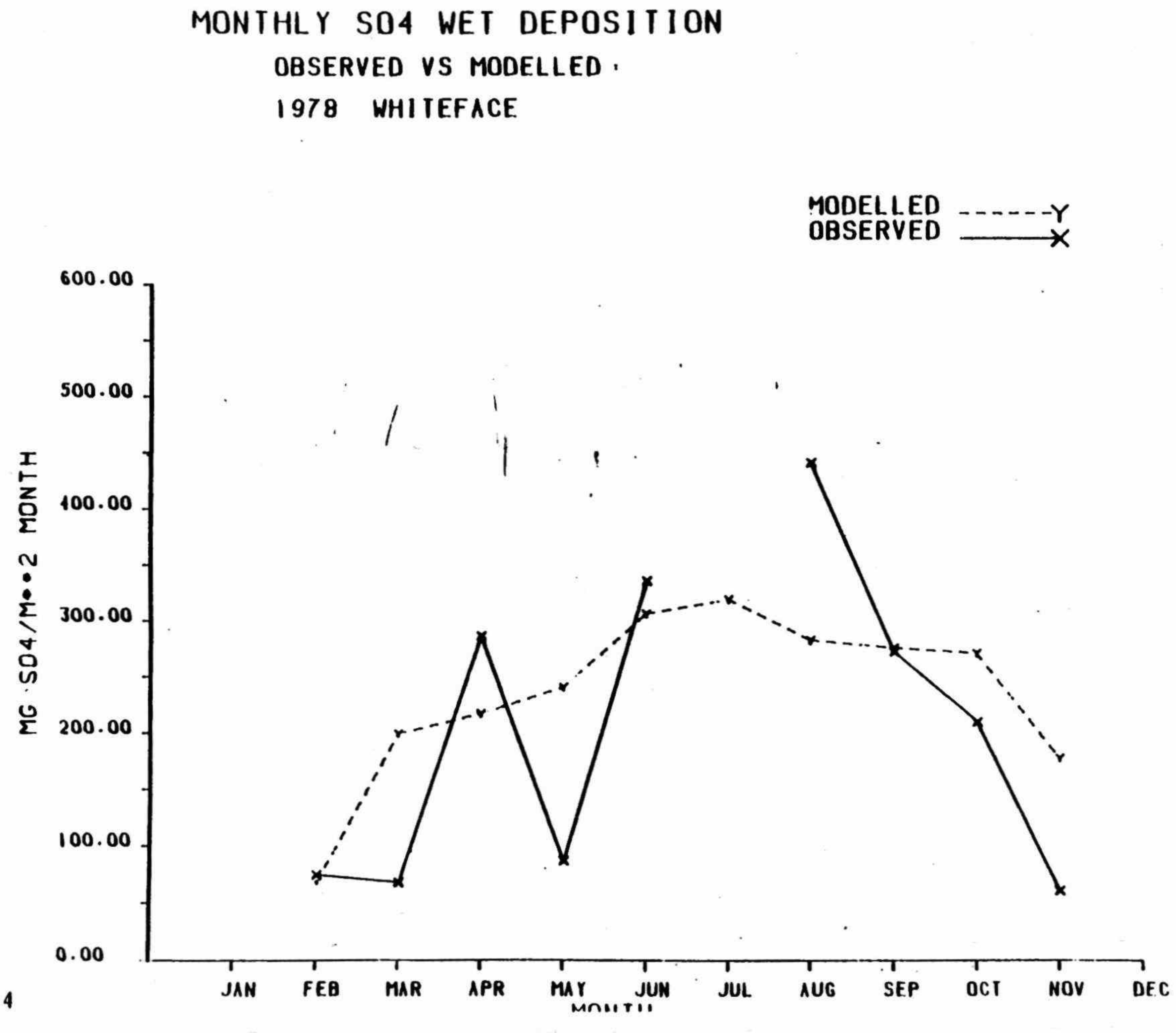

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1978 WHITEFACE
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 4

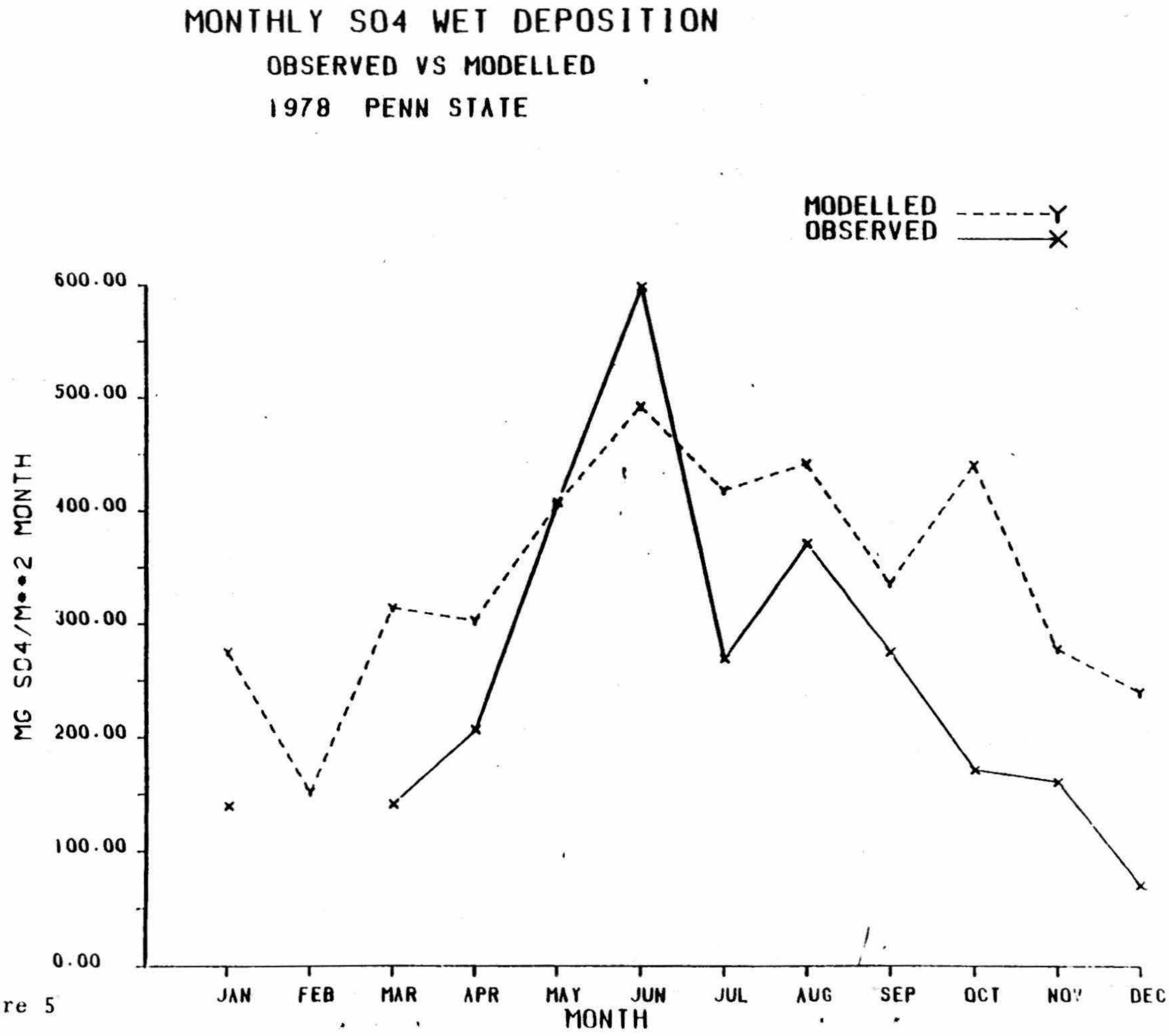
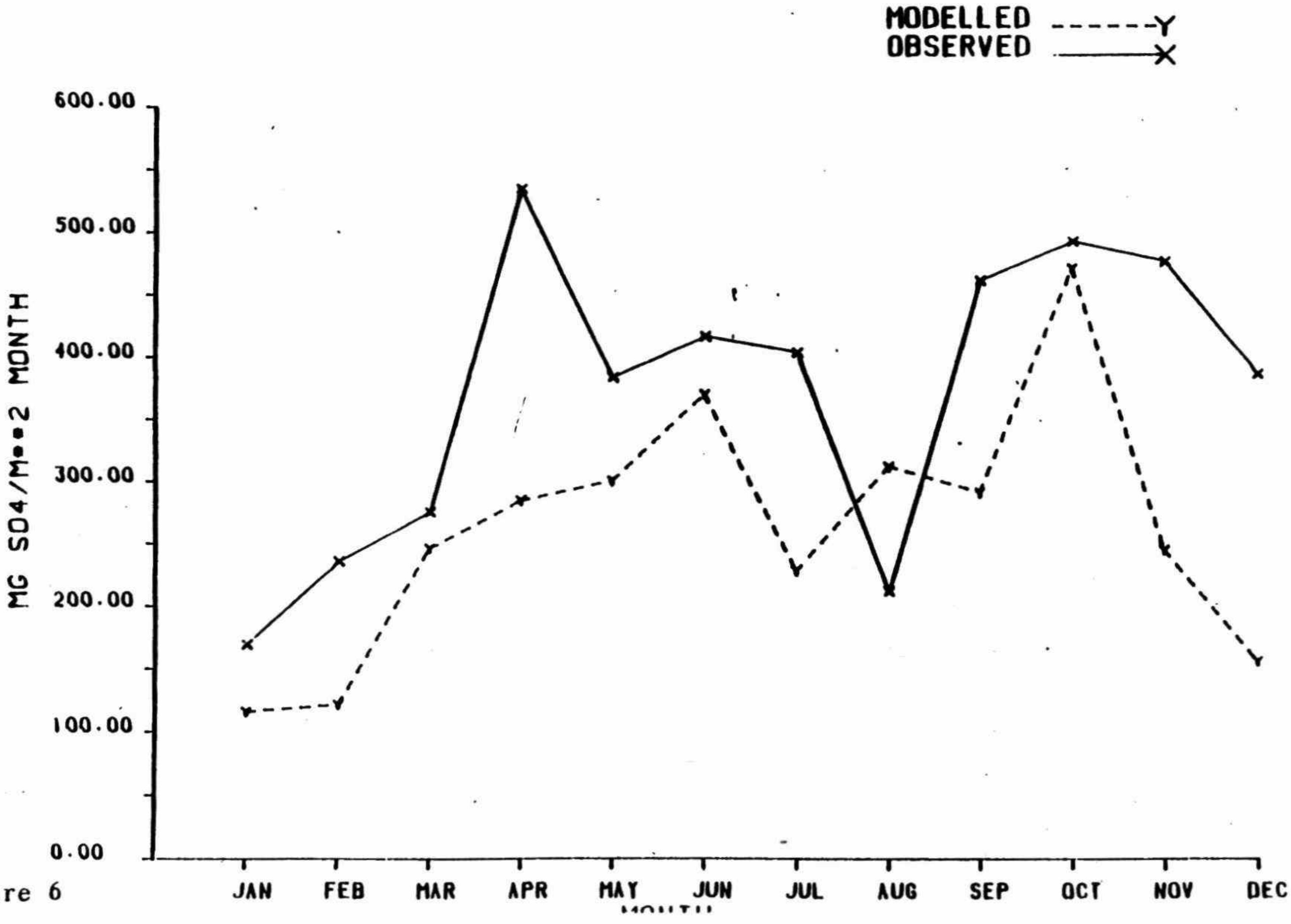

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1978 PENN STATE
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 5

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 PARRY SOUND



igure 6

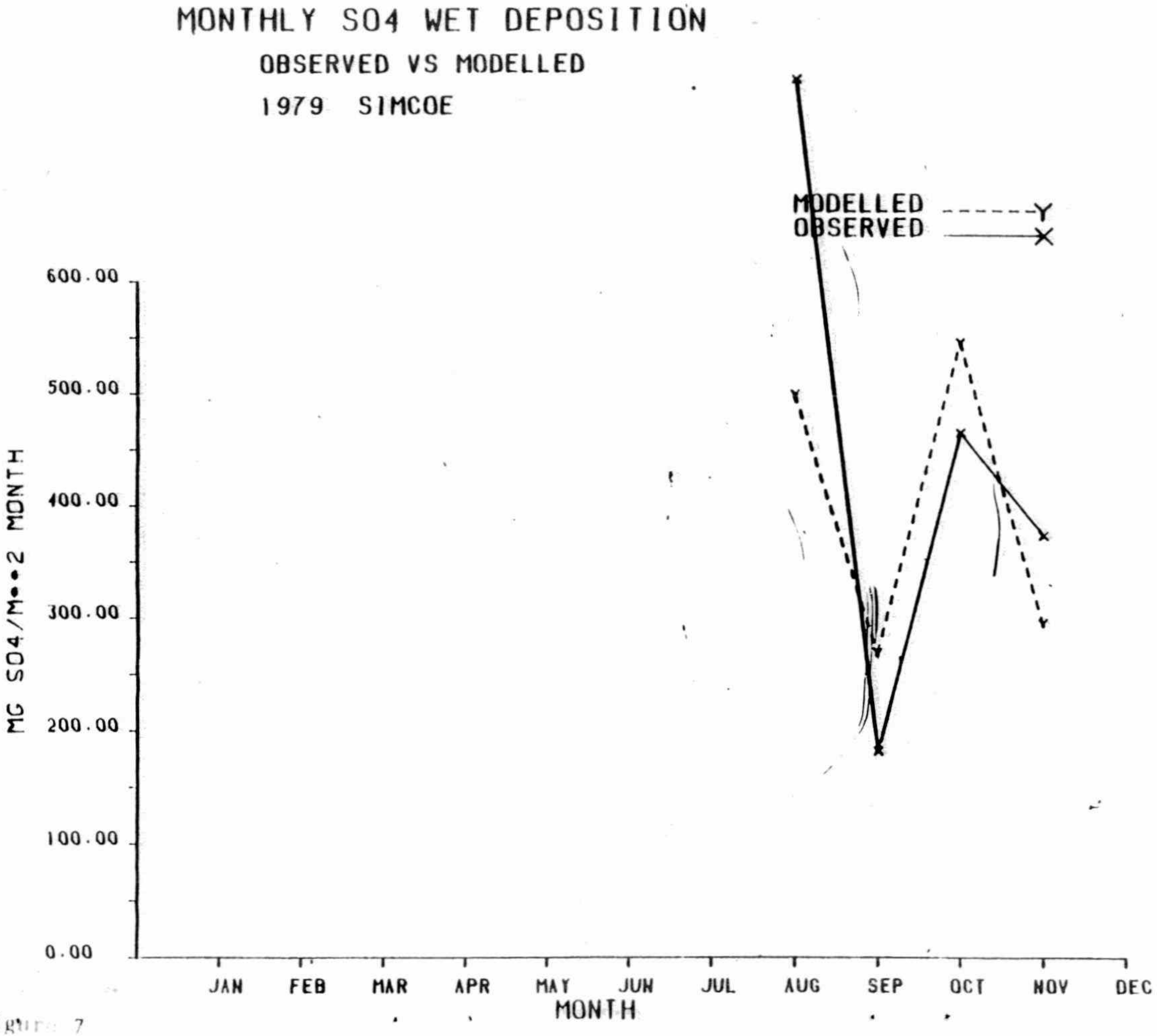

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 SIMCOE
MODELLED Y
OBSERVED X
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 7

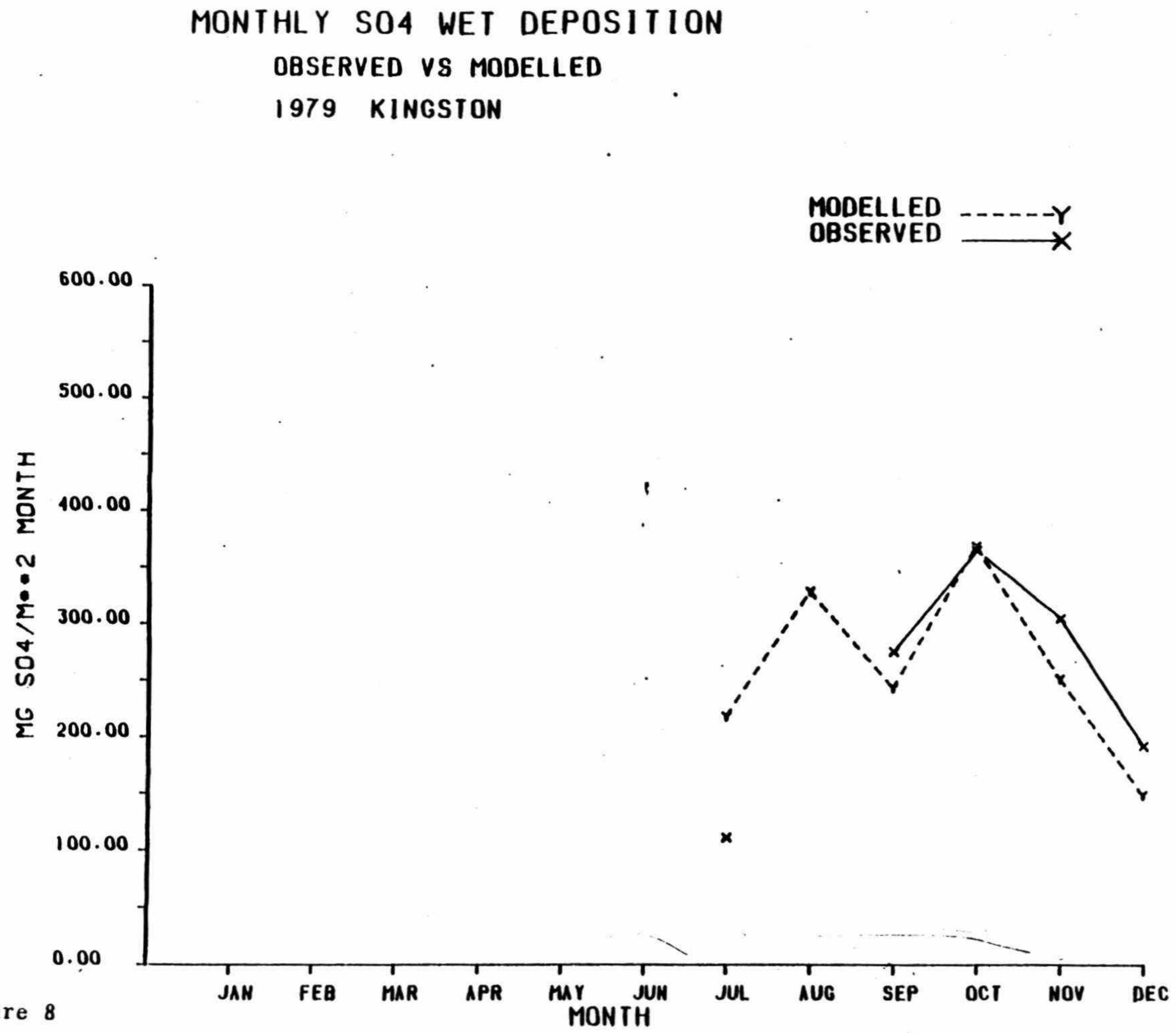
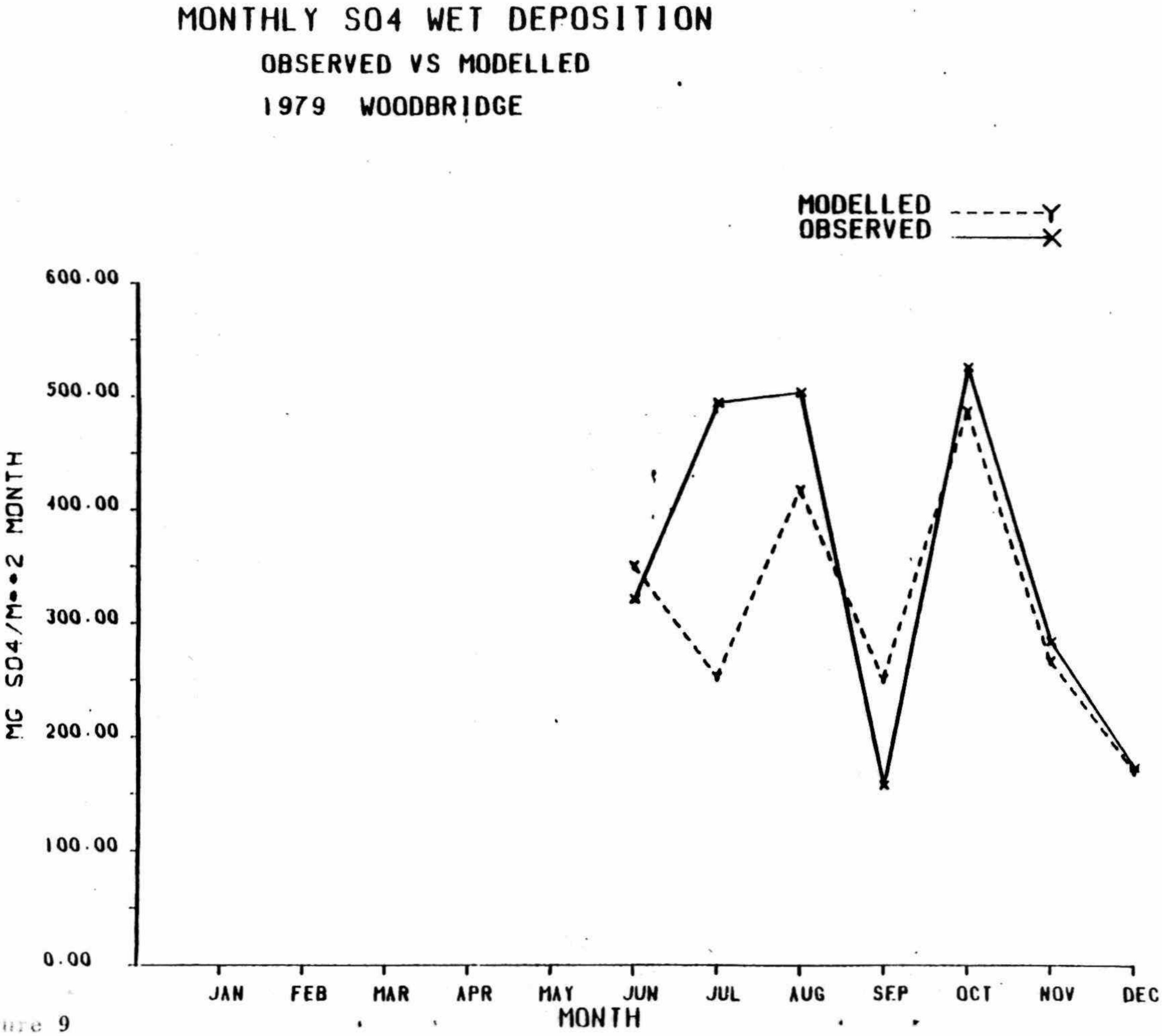

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 KINGSTON
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 8



MONTHLY SO4 WET DEPOSITION

OBSERVED VS MODELLED

1979 WOODBRIDGE

Figure 9

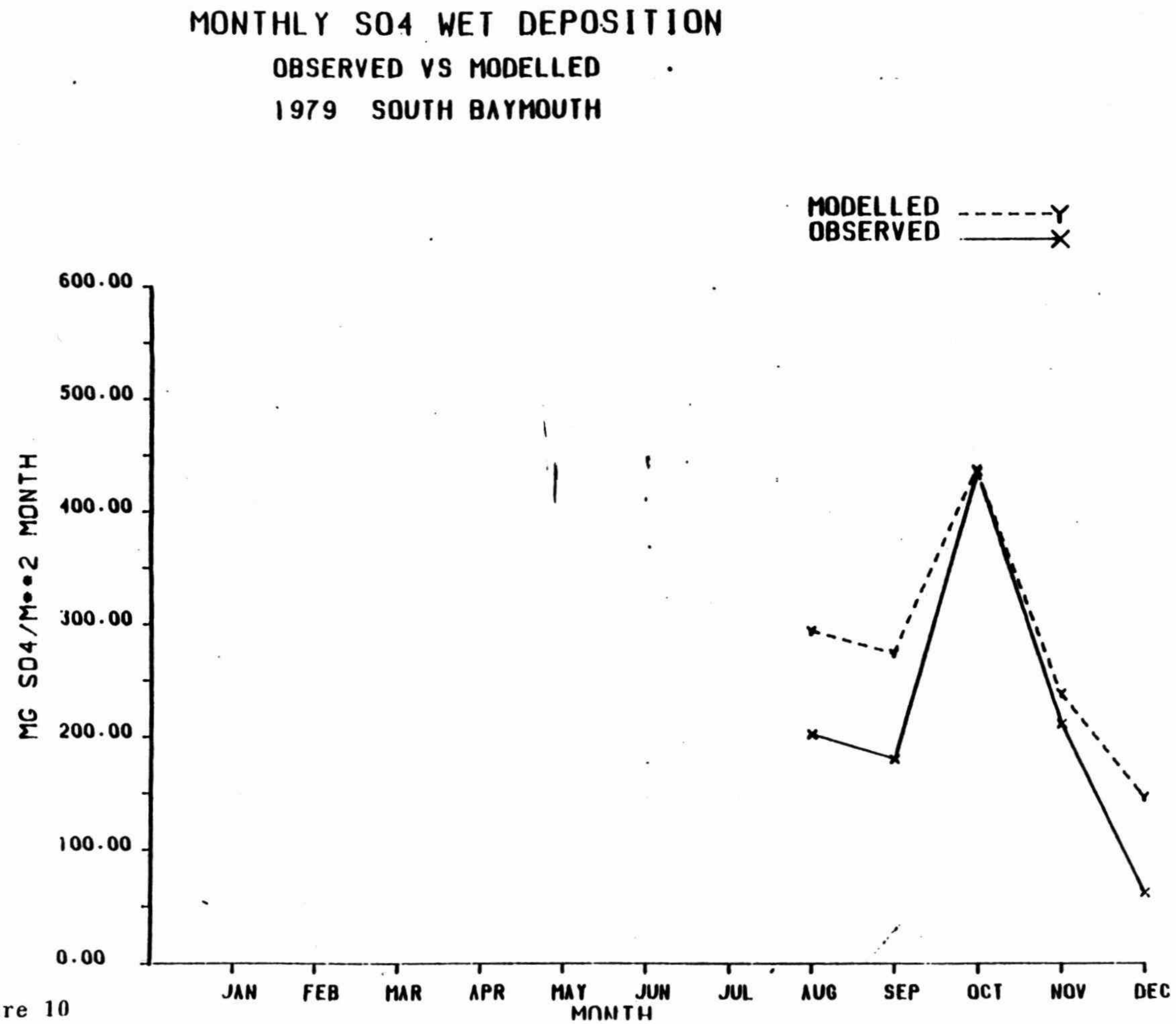

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 SOUTH BAYMOUTH
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 10

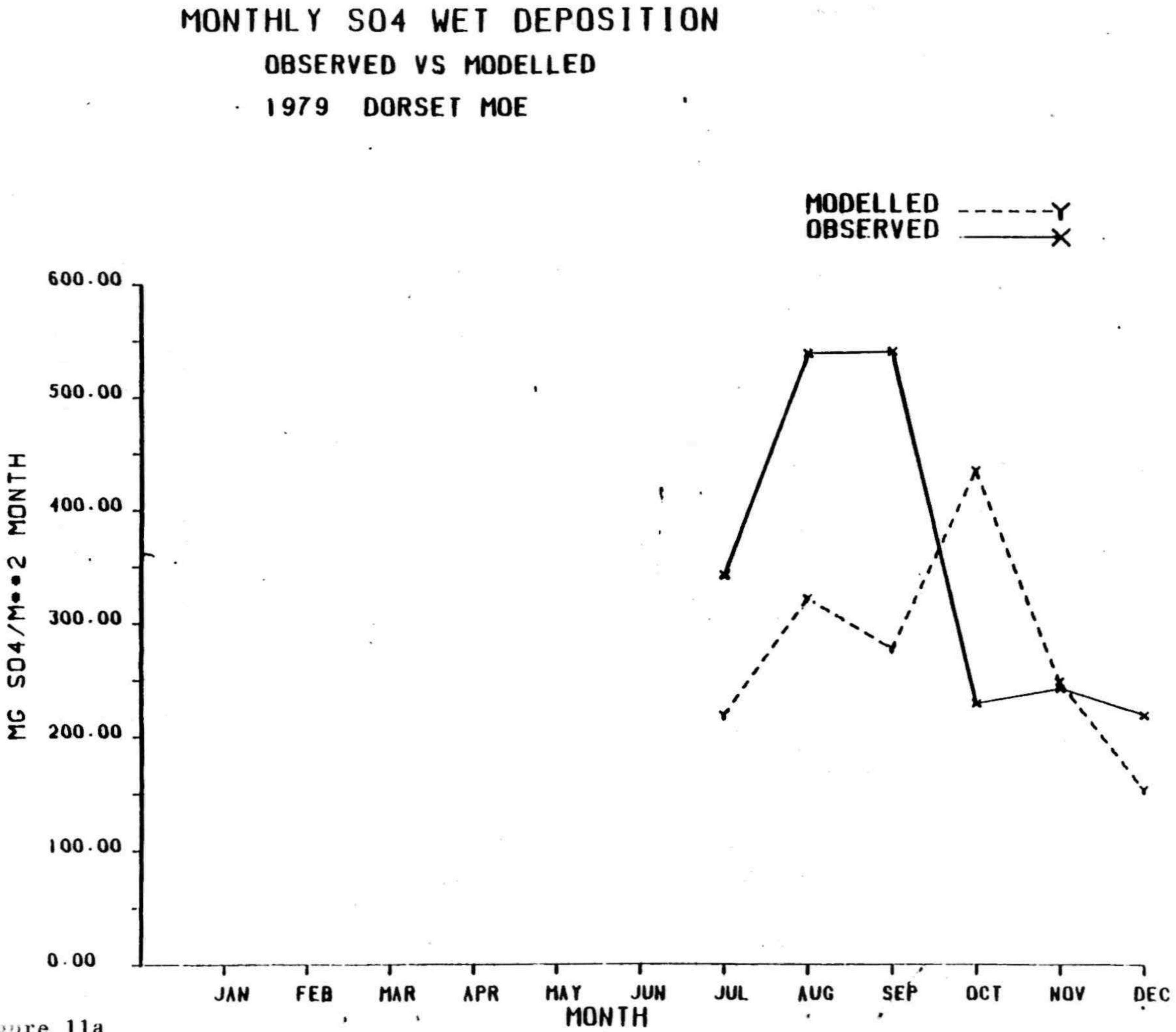

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 DORSET MOE
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M••2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 11a

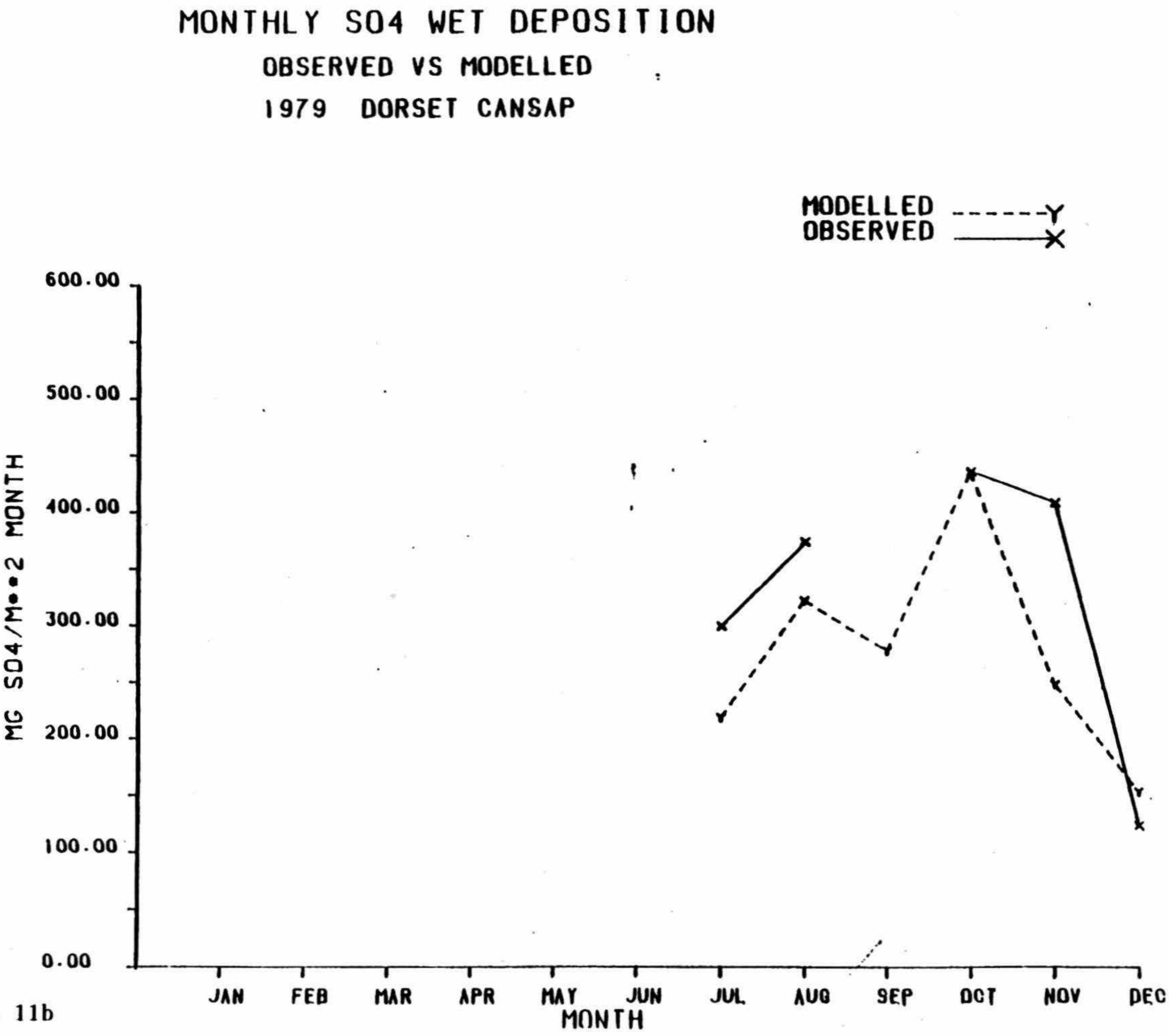

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 DORSET CANSAP
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 11b

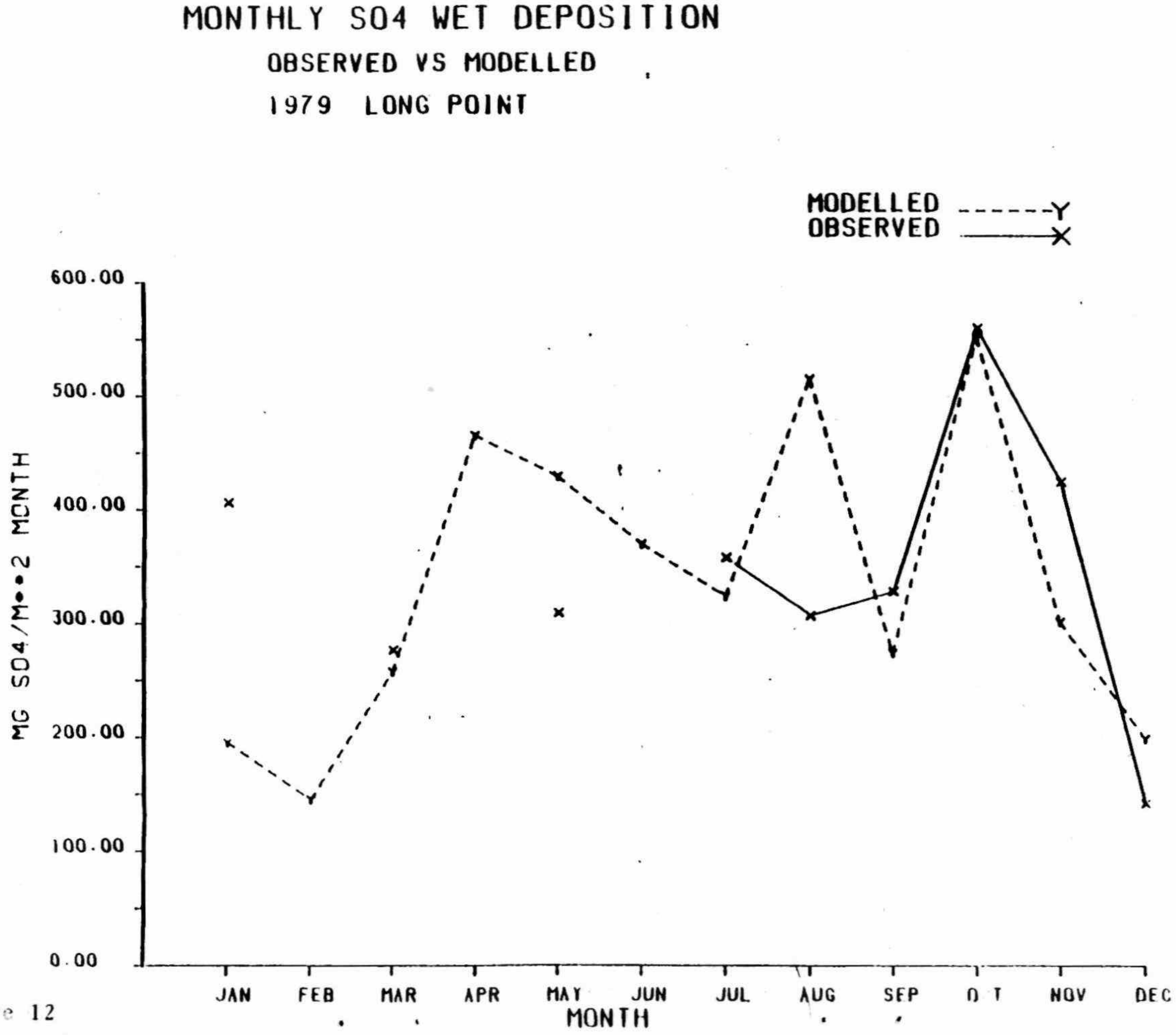

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 LONG POINT
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 12

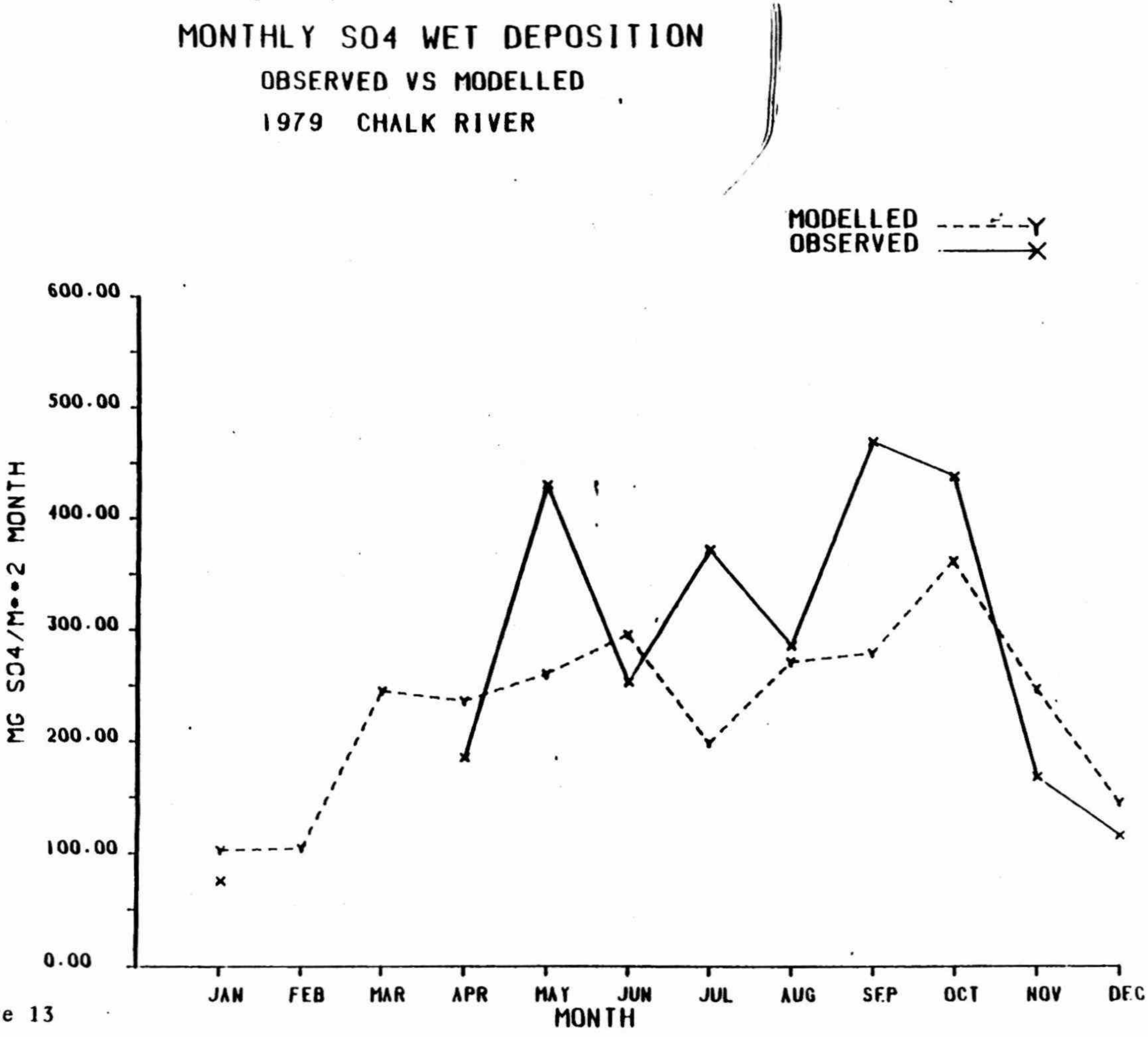

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 CHALK RIVER
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 13

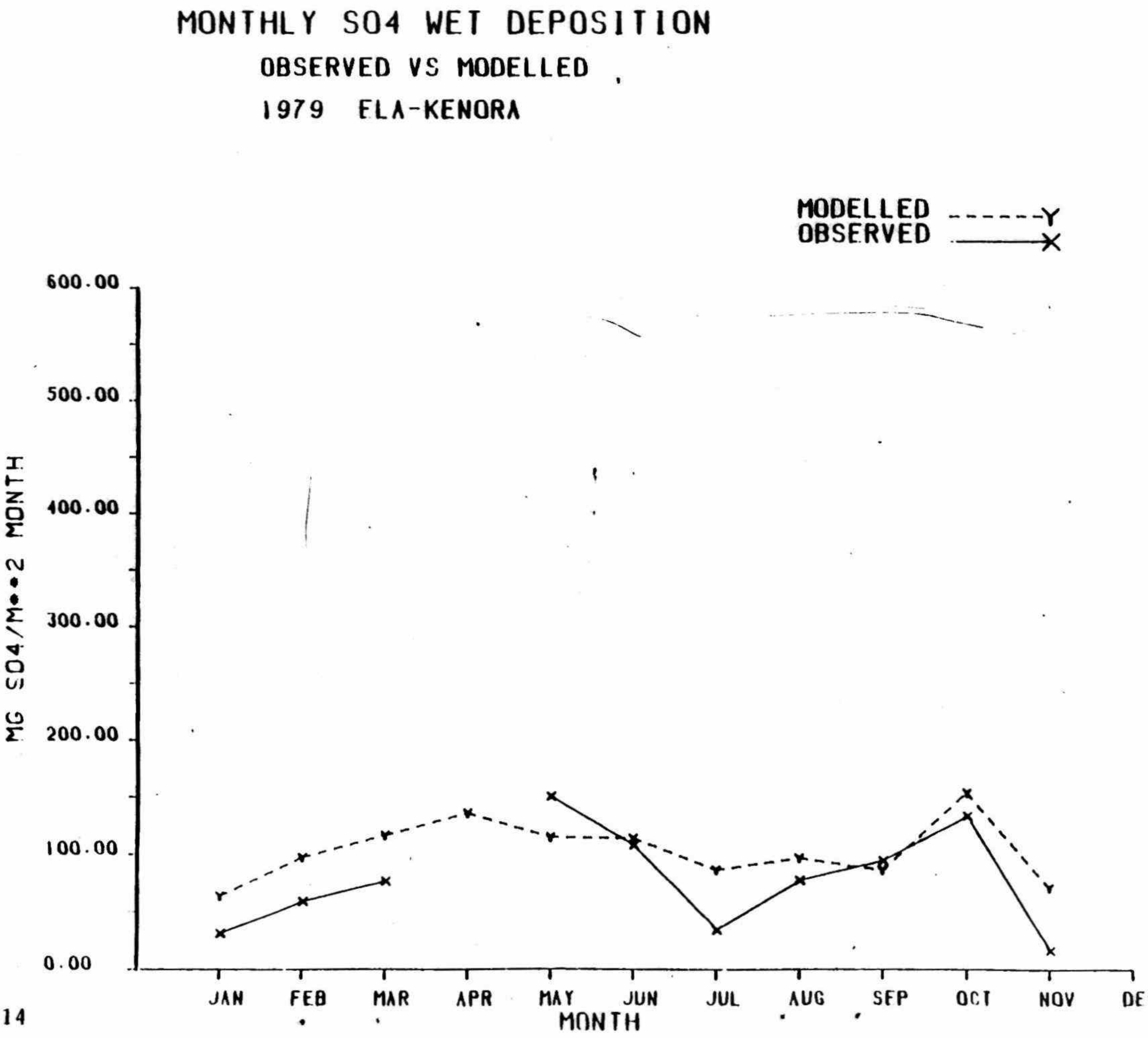
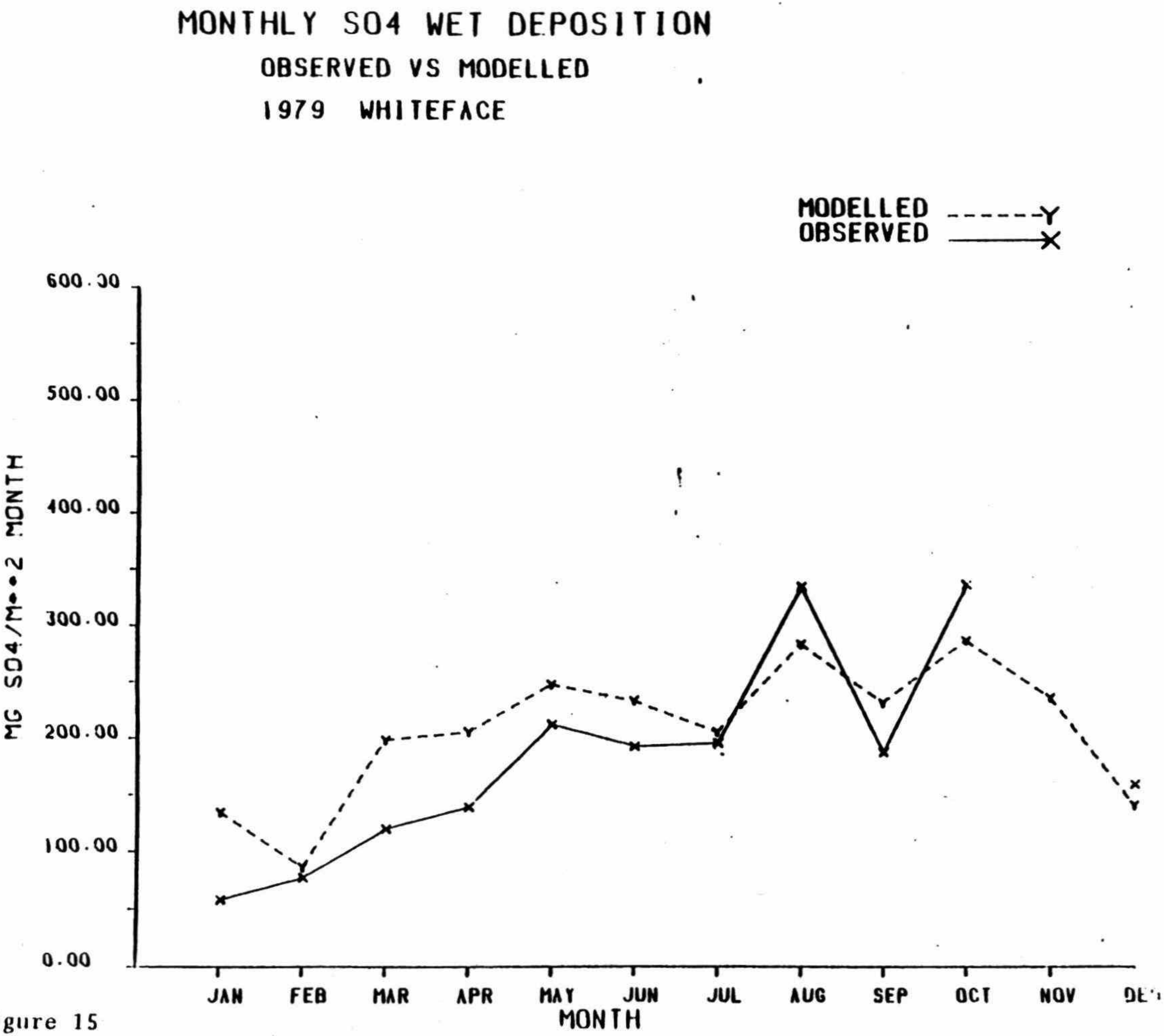

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 ELA-KENORA
MODELLED Y
OBSERVED X
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 14



MONTHLY SO4 WET DEPOSITION

OBSERVED VS MODELLED

1979 WHITEFACE

Figure 15

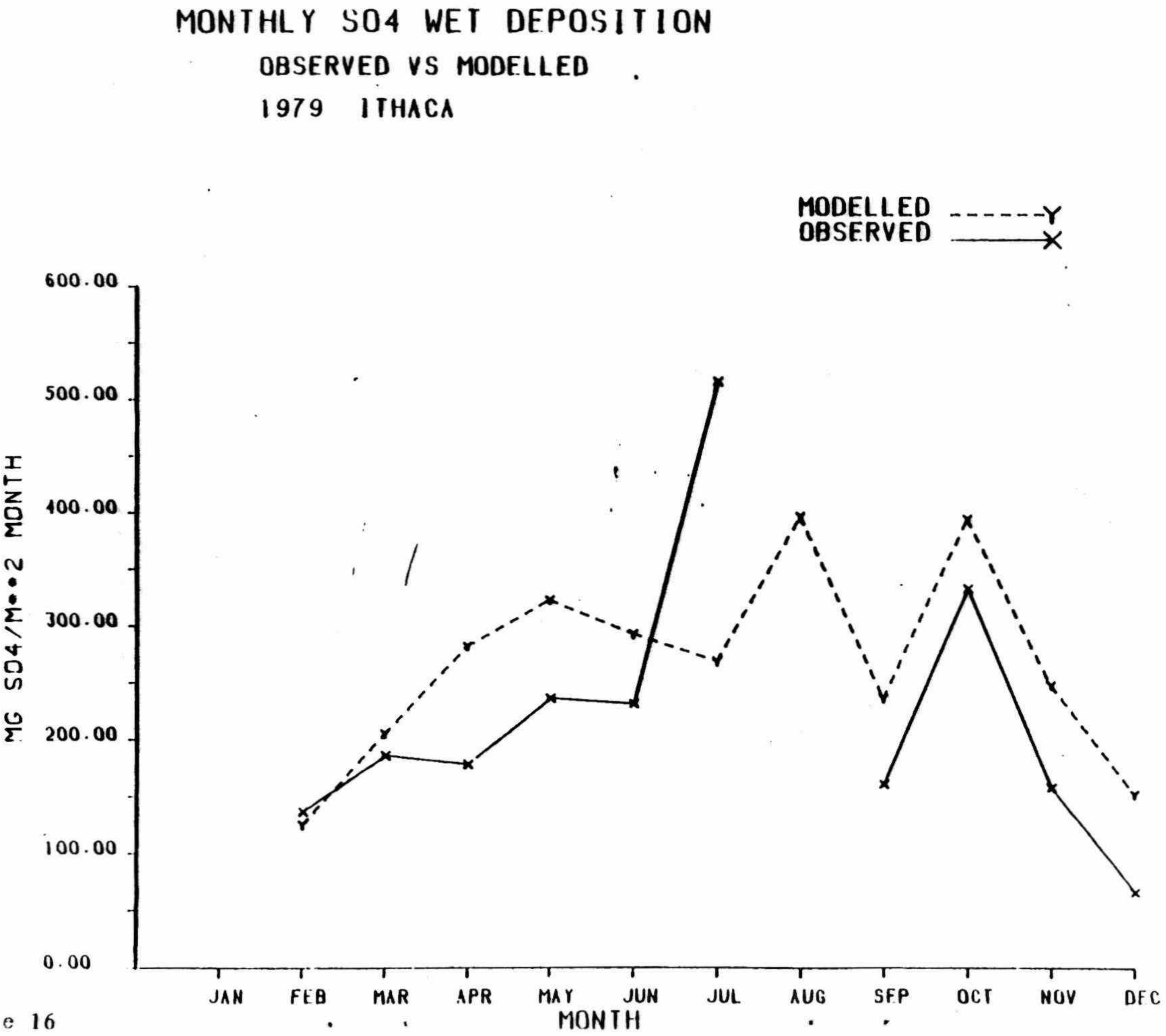

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 ITHACA

Figure 16

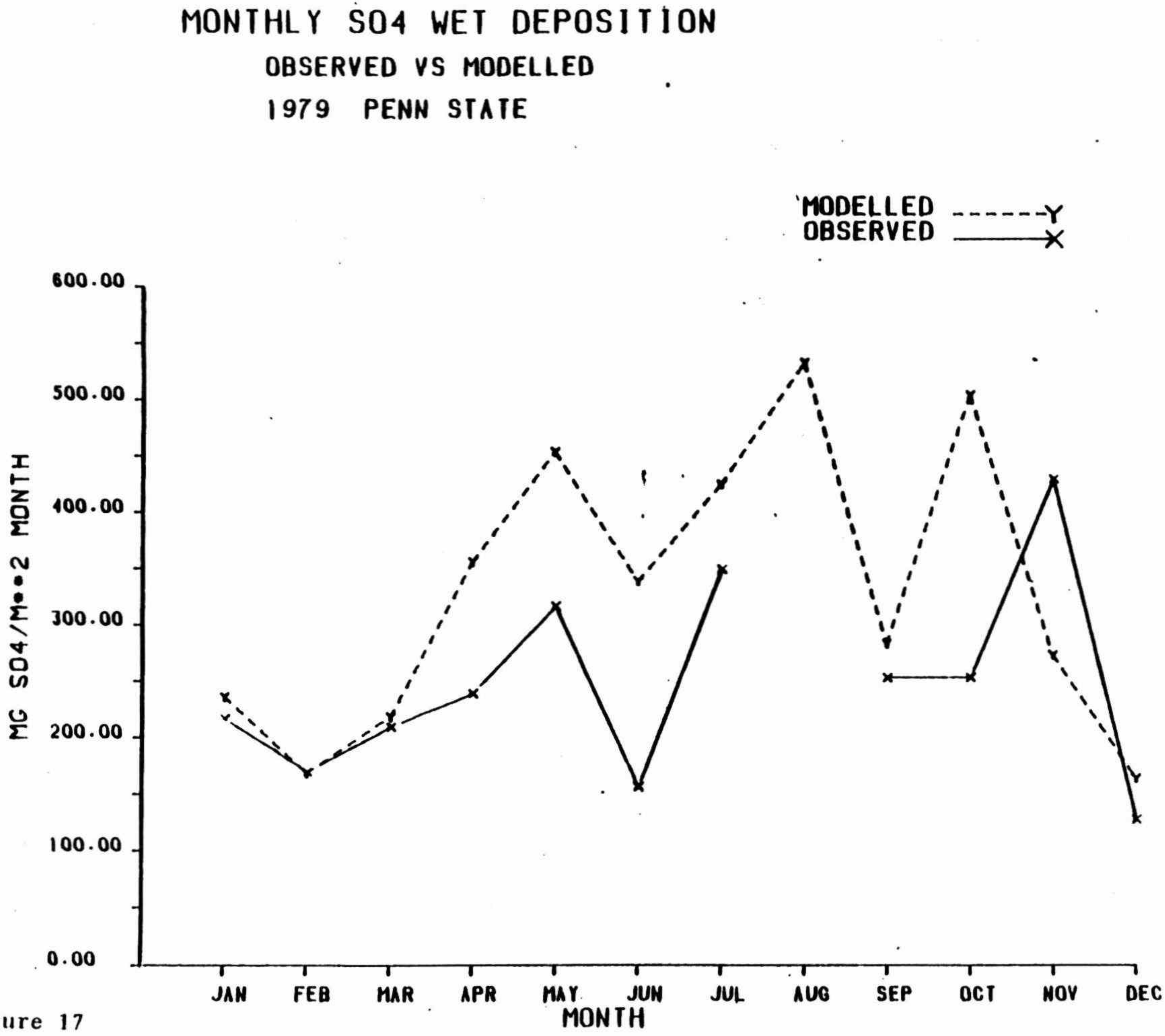

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 PENN STATE
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 17

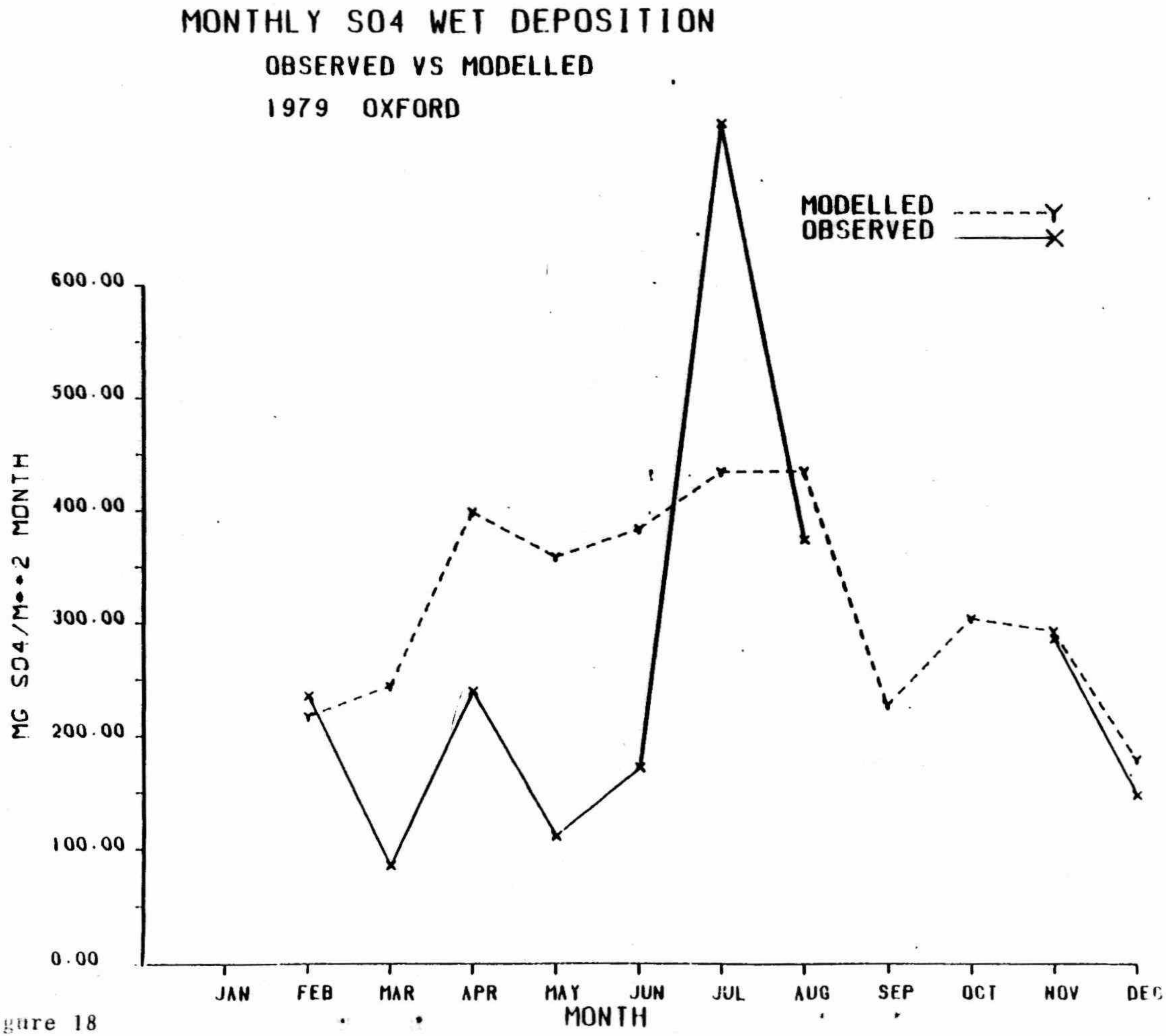

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1979 OXFORD
MODELLED
OBSERVED
MG SO4/M**2 MONTH
600.00
500.00
400.00
300.00
200.00
100.00
0.00
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 18

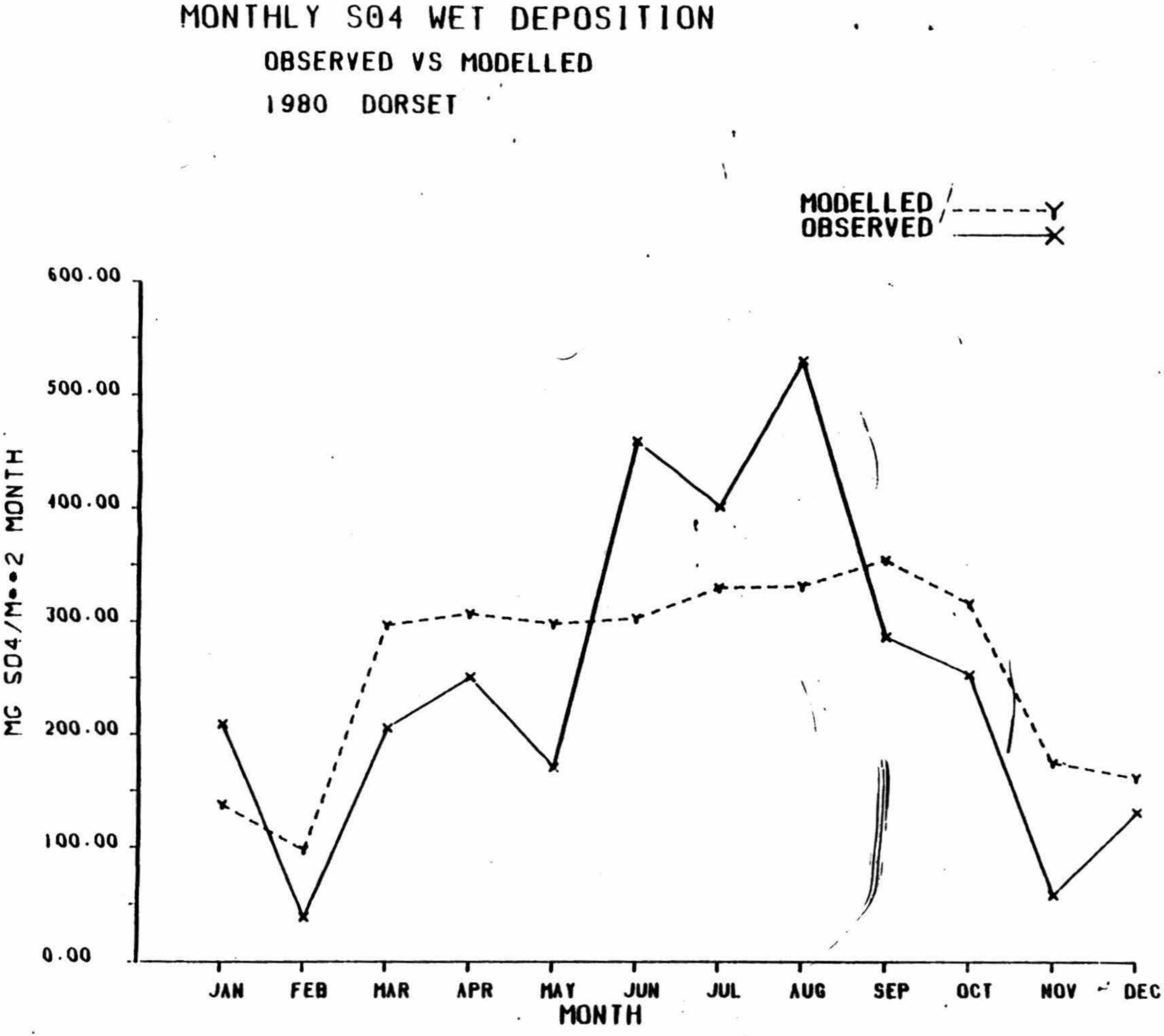
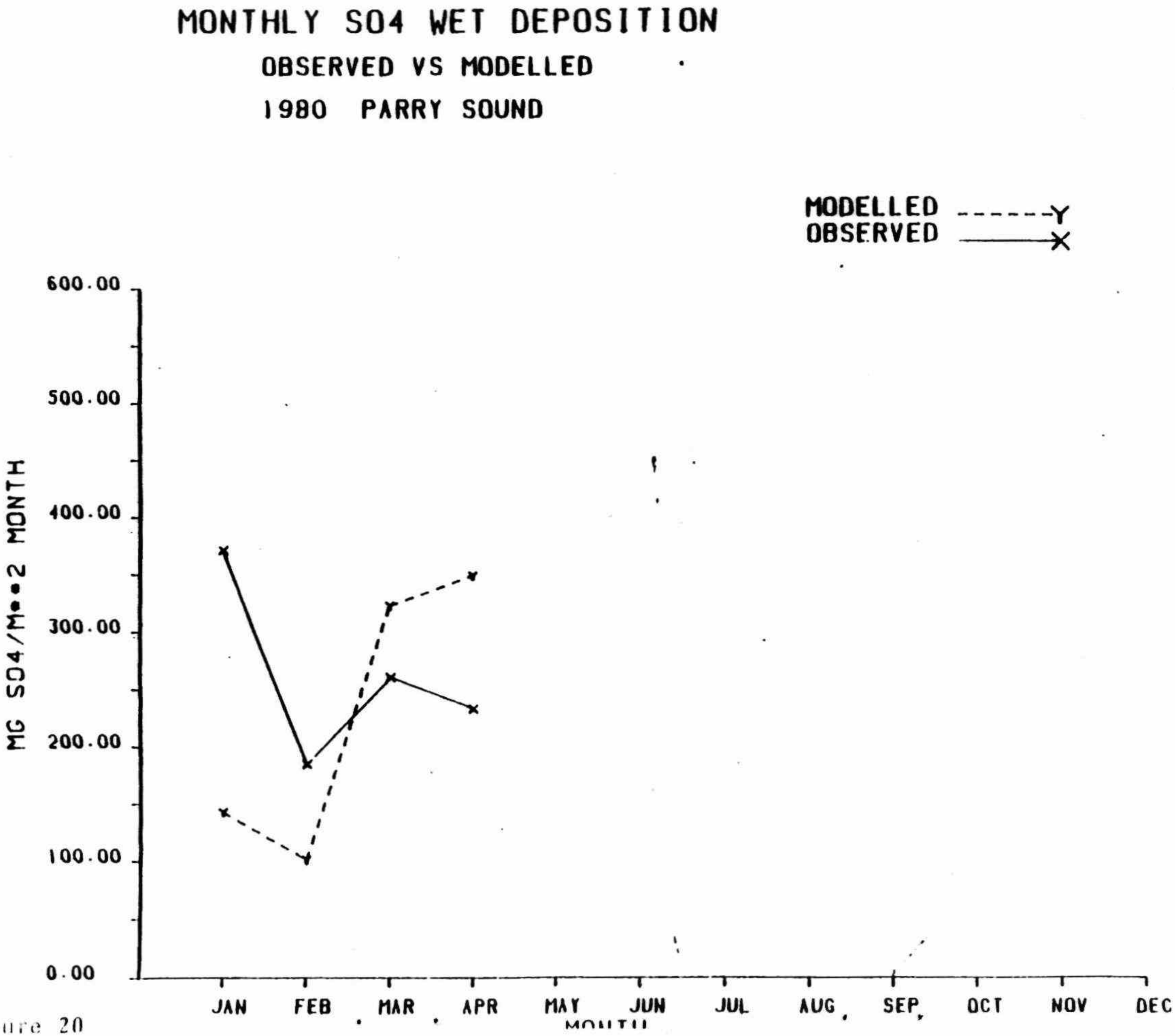

MONTHLY S04 WET DEPOSITION
OBSERVED VS MODELLED
1980 DORSET
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 19



MONTHLY SO4 WET DEPOSITION

OBSERVED VS MODELLED

1980 PARRY SOUND

Figure 20

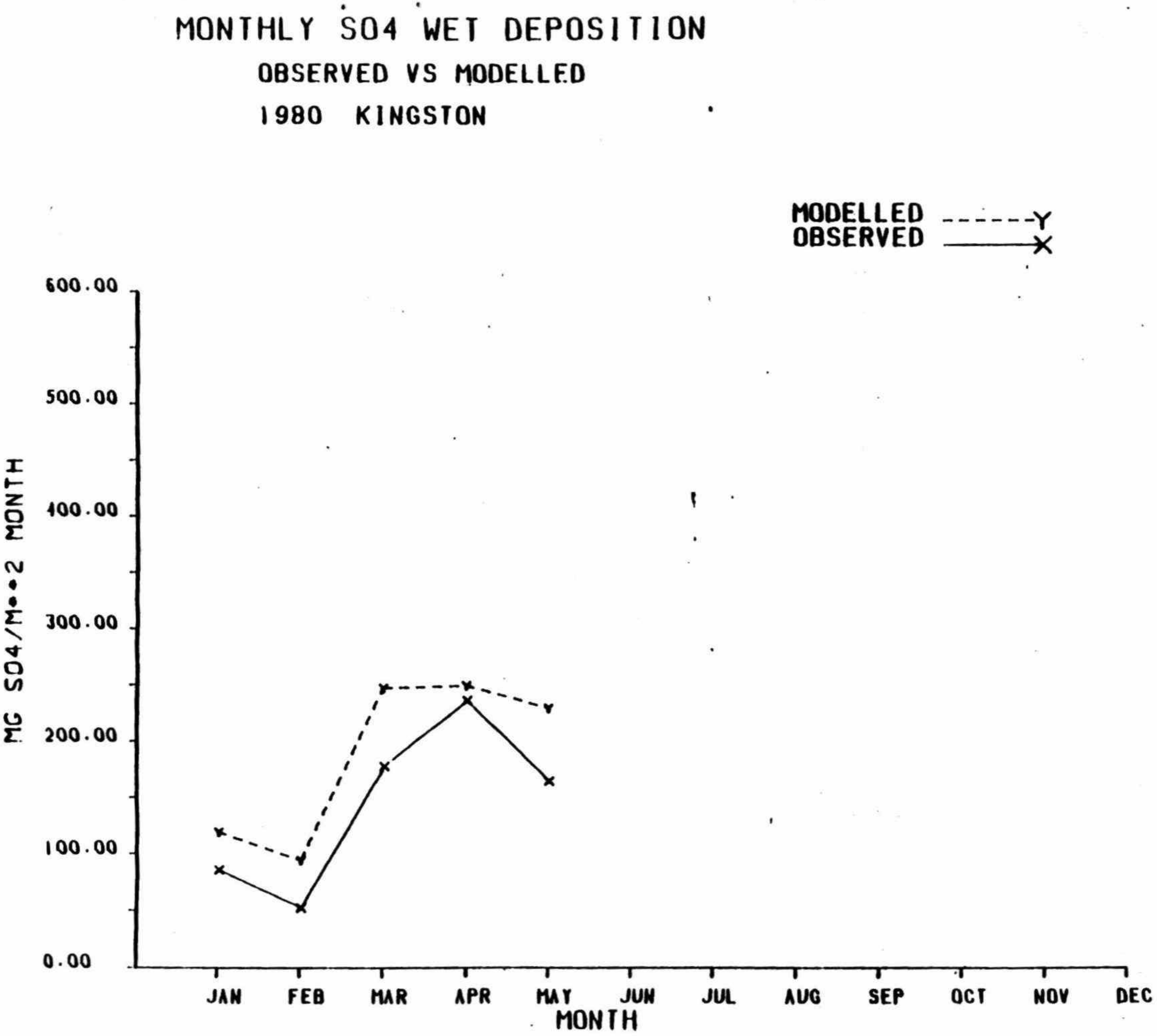

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1980 KINGSTON
MODELLED Y
OBSERVED X
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 21

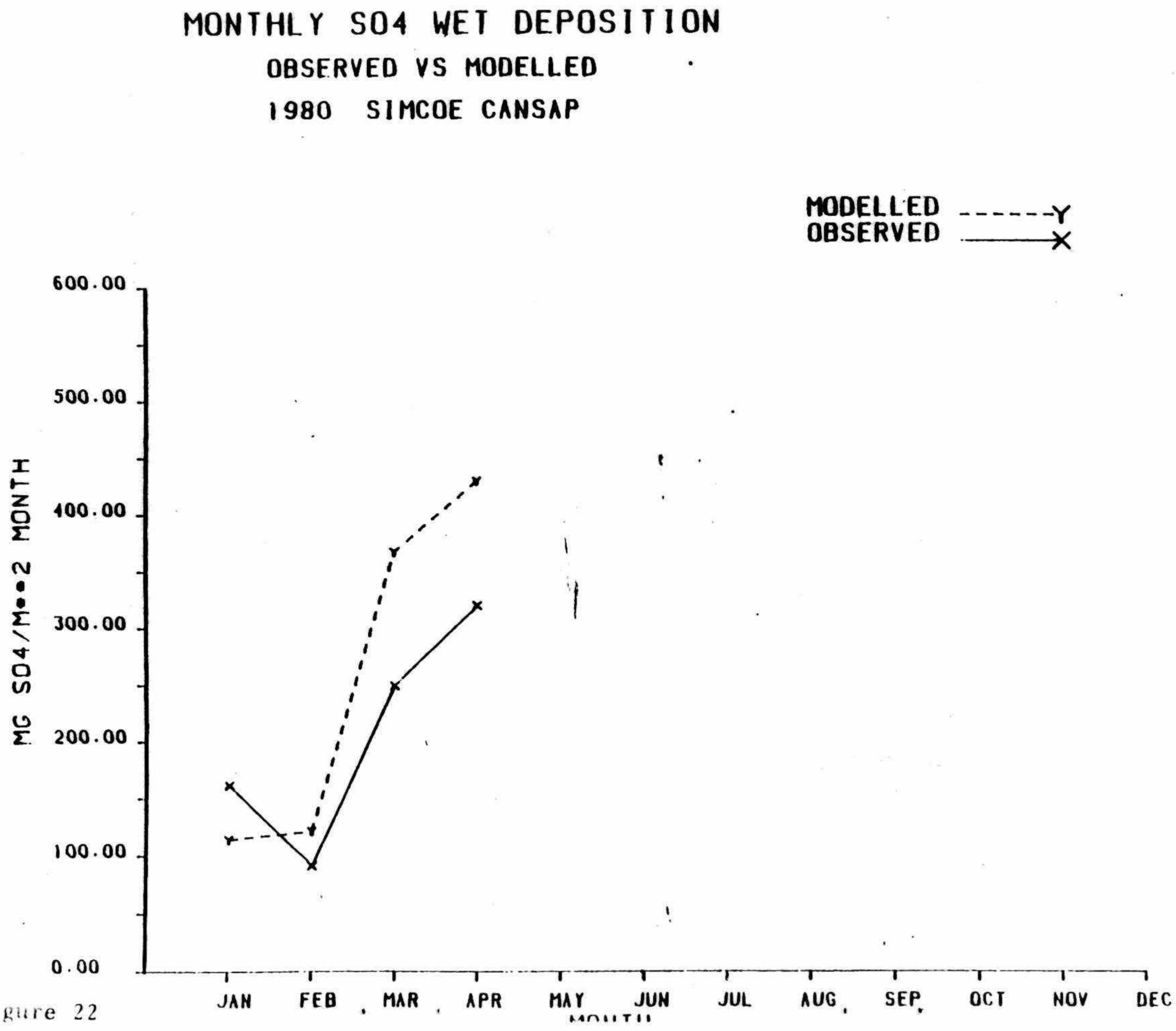

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1980 SIMCOE CANSAP
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 22

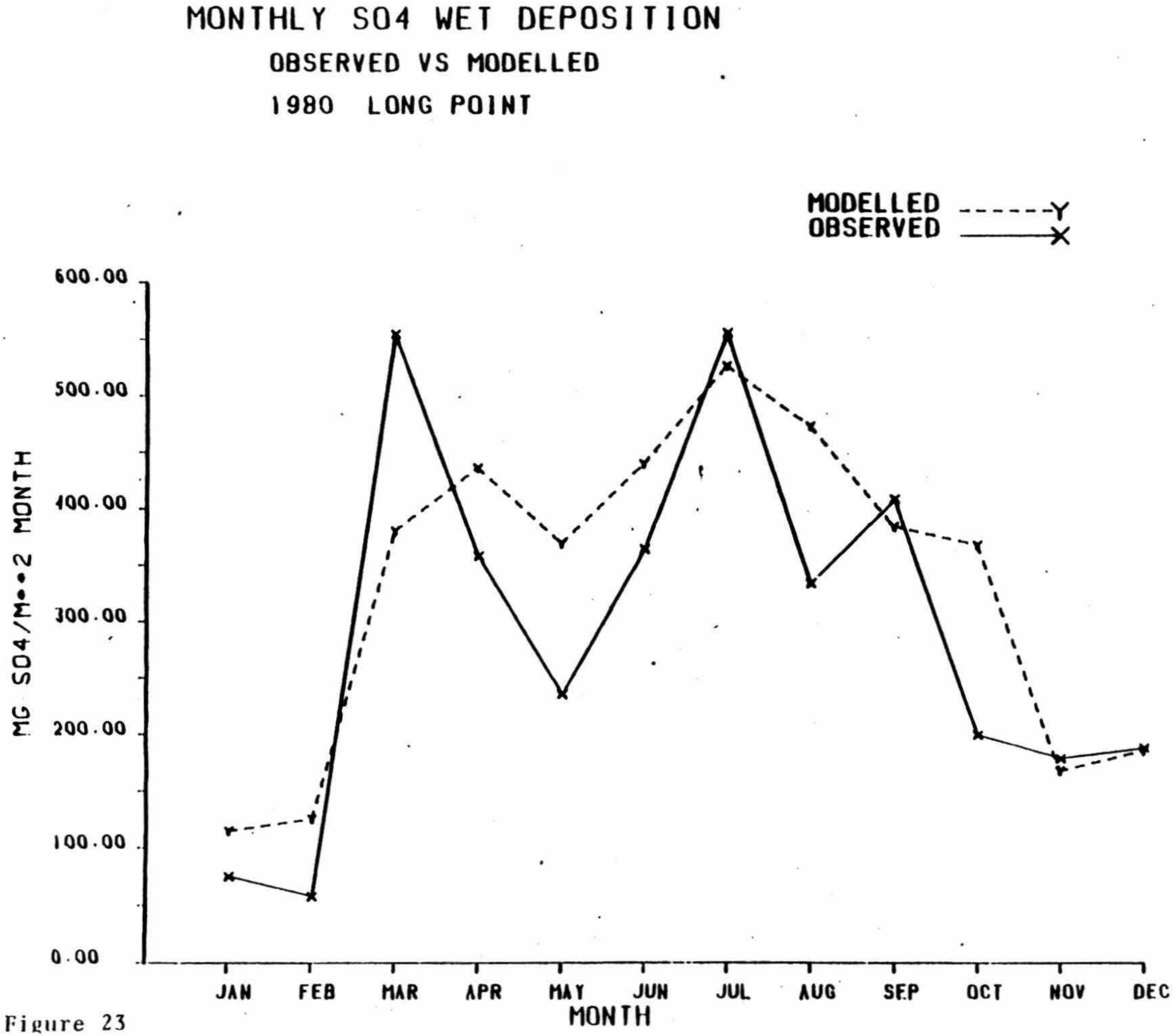

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1980 LONG POINT
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 23

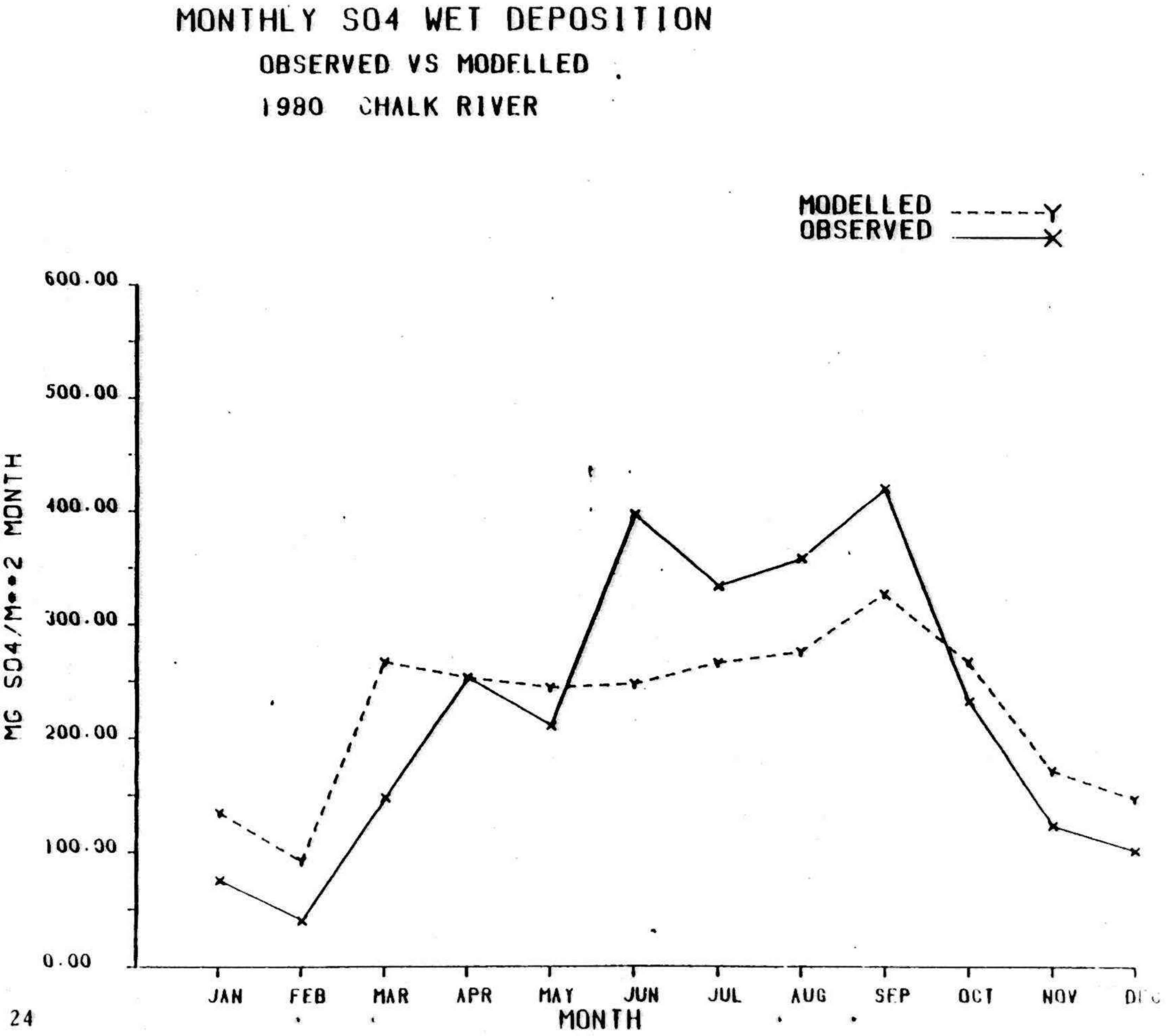

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1980 CHALK RIVER
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 24

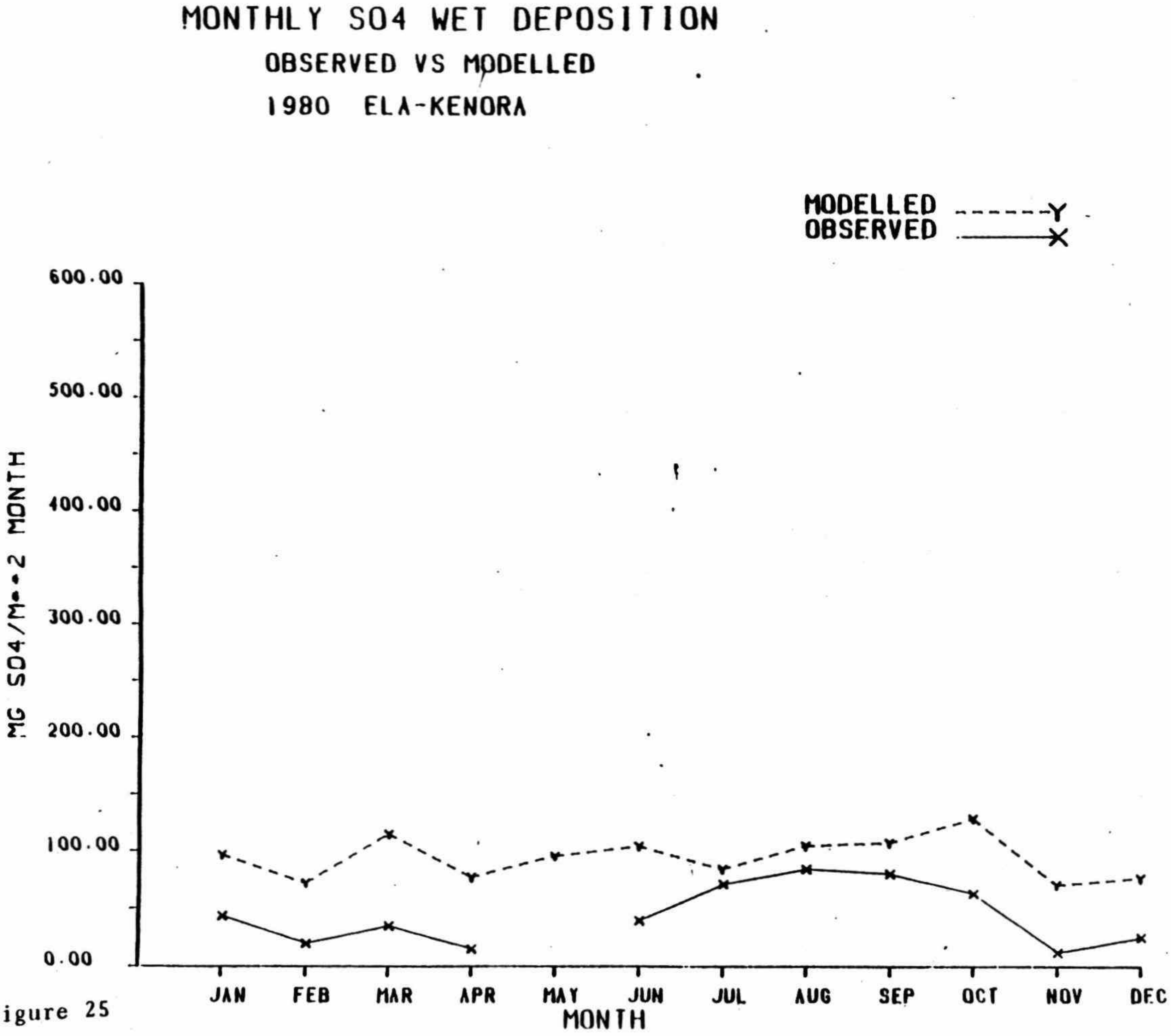

MONTHLY SO4 WET DEPOSITION
OBSERVED VS MODELLED
1980 ELA-KENORA
MODELLED
OBSERVED
600.00
500.00
400.00
300.00
200.00
100.00
0.00
MG SO4/M**2 MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

Figure 25

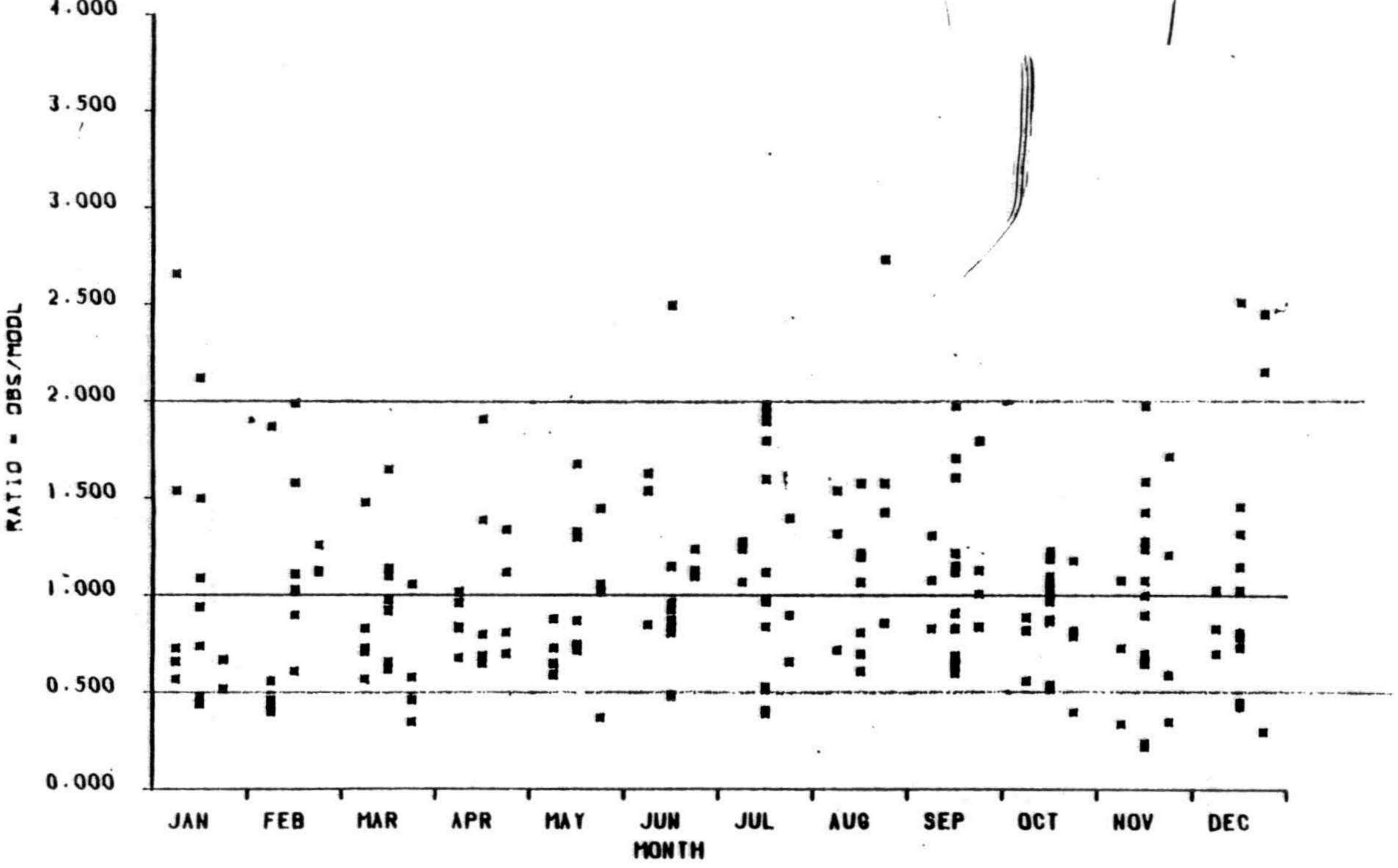


Figure 26 Ratio of measured:modelled monthly wet deposition of sulphur; background of 50 mg SO_4/m^2. month included in model values.

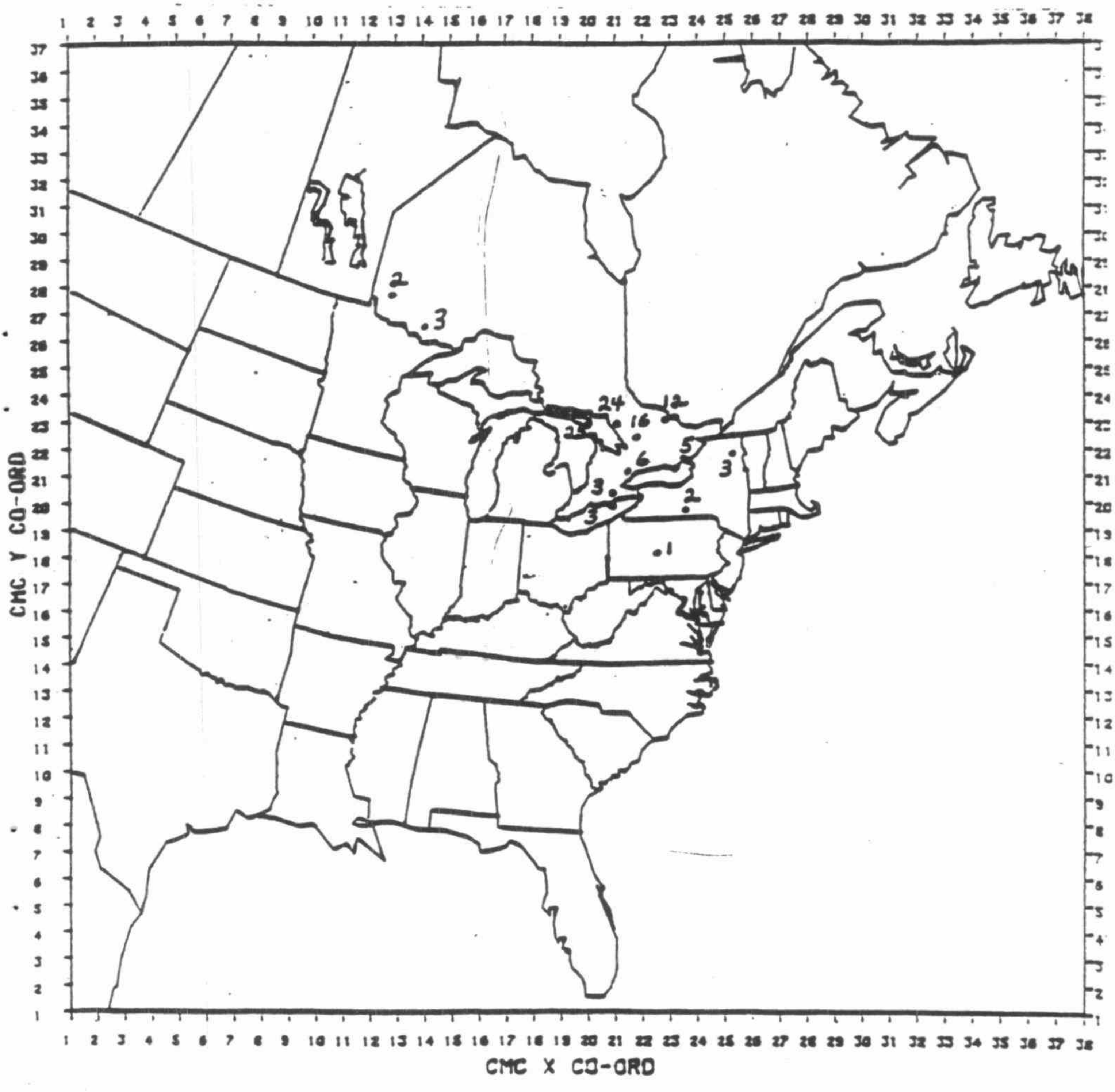


Figure 27 Model estimate of percentage reduction in wet deposition of sulphate due to INCO strike/shutdown period in 1979.

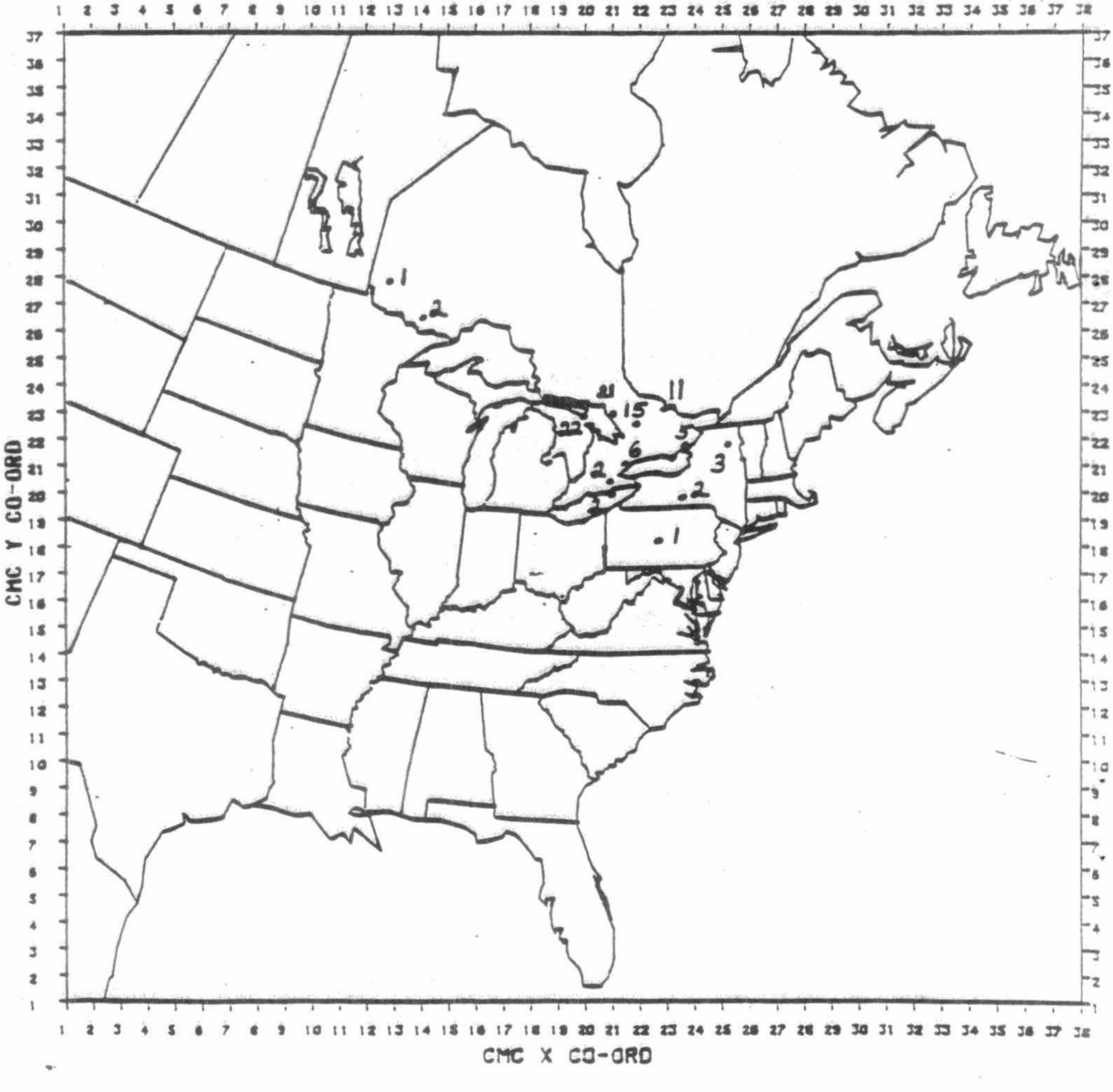


Figure 28 Model estimate of percentage reduction in wet deposition of sulphate if INCO emissions were reduced to zero in three year period 1978 - 1980.

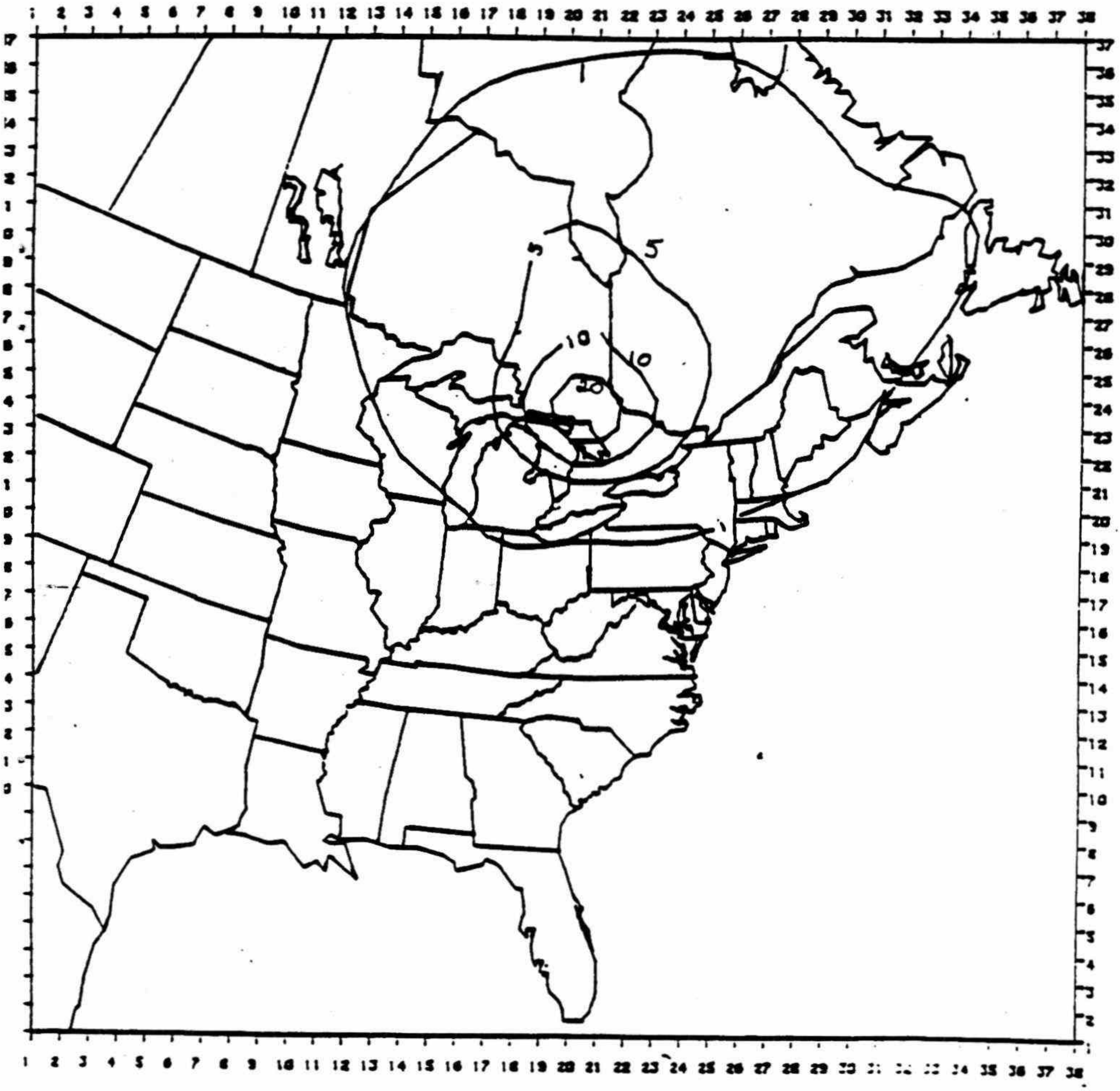


Figure 29: Model estimate of the percentage reduction in wet deposition of sulphur for a model experiment in which Inco emissions were simulated as operating and non-operating while all other emissions and meteorological conditions were kept constant, for the year 1980.

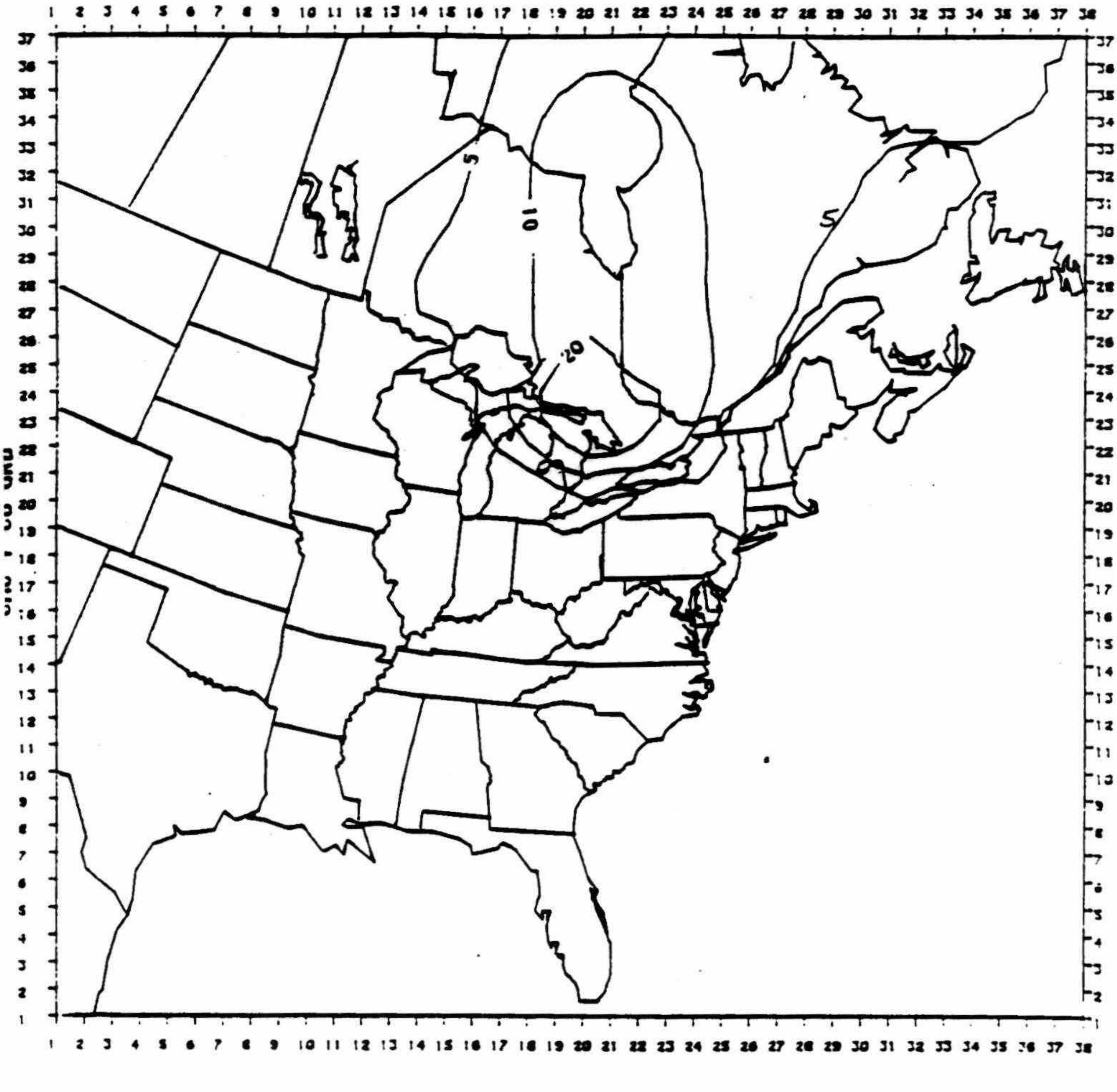


Figure 30: Model estimate of the percentage reduction in dry deposition of sulphur dioxide for a model experiment in which Inco emissions were simulated as operating and non-operating while all other emissions and meteorological conditions were kept constant, for the year 1980.

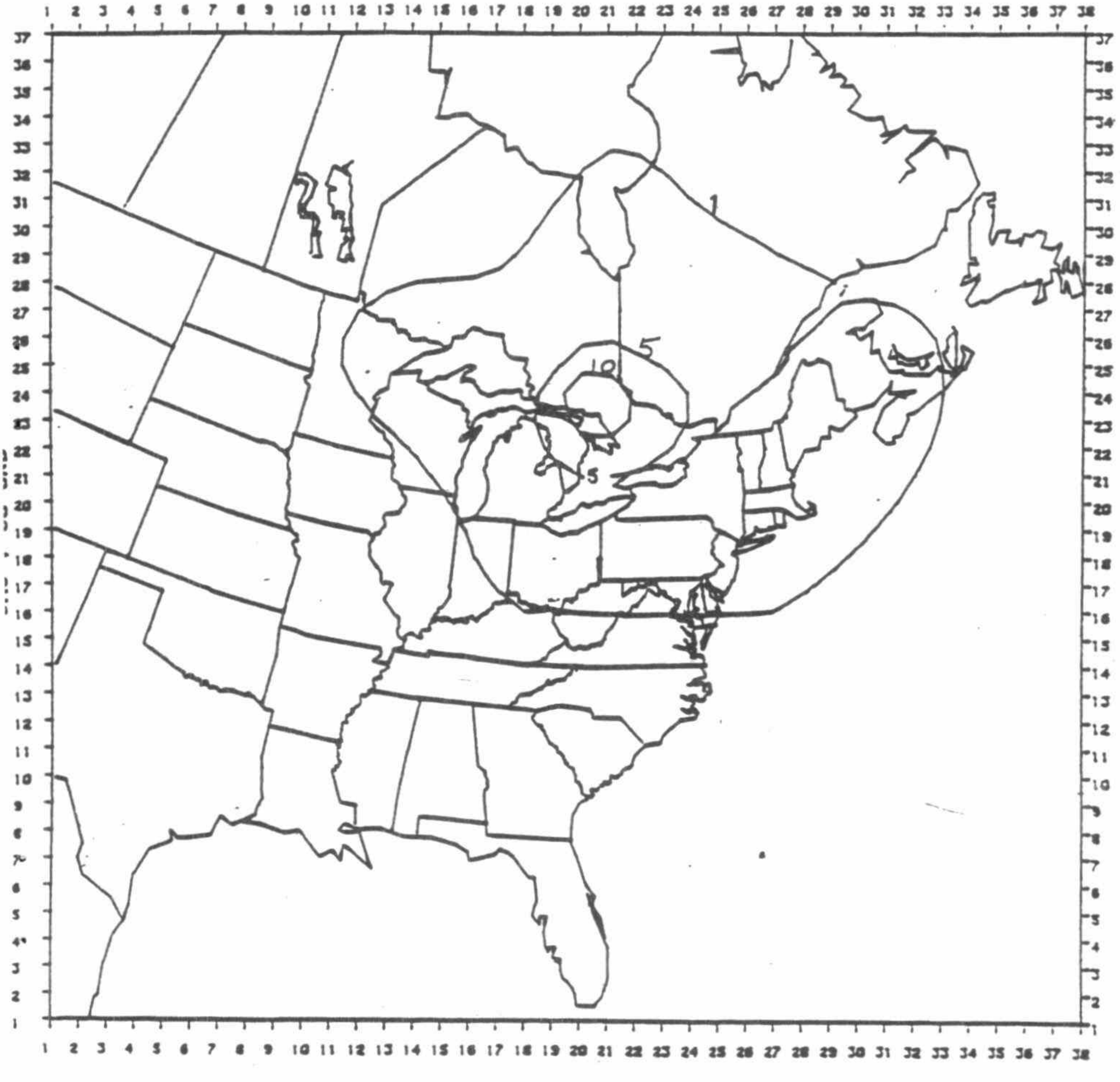


Figure 31: Model estimate of the percentage reduction in dry deposition of sulphates for a model experiment in which Inco emissions were simulated as operating and non-operating while all other emissions and meteorological conditions were kept constant, for the year 1980.

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Examination of monthly wet sulphate deposition by a lagrangian model and its application to study the effects

40240